OCEANOBS'19: AN OCEAN OF OPPORTUNITY. VOLUME II

EDITED BY: Tong Lee, Sabrina Speich, Laura Lorenzoni, Sanae Chiba, Frank E. Muller-Karger, Minhan Dai, Amos T. Kabo-Bah, John Siddorn, Justin Manley, Maria Snoussi and Fei Chai

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OCEANOBS'19: AN OCEAN OF OPPORTUNITY.
VOLUME II

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Cover and introductory image by Consortium for Ocean Leadership.

This eBook contains peer-reviewed community white papers (CWPs) as part of the community inputs to the OceanObs'19 Conference. The OceanObs conferences are held once every ten years for the scientific, technical, and operational communities involved in the planning, implementation, and use of ocean observing systems. The goal of the conferences is to communicate progress, promote plans, and to define advances to ocean observing system in response to societies' needs. Each conference provides a forum for the community to review the state of the ocean observing science and operations, and to define goals and plans to achieve over the next decade. The OceanObs'19 conference is the third in the series. It seeks to further align the science, technology, and human capacity of ocean observing to address growing and urgent societal needs.

CWPs have always been an integral part of the OceanObs conference series. The objective of this OceanObs'19 Research Topic in Frontiers in Marine Science is to provide a forum for community recommendations to inform the outcome of OceanObs'19 conference and to guide post-conference actions. The 140 CPWs collected under this Research Topic encompass perspectives from interested groups, including science, operational and commercial end-users, and stakeholders, on the needs and aspirations for the coming decade. Over 2500 authors from 79 countries contributed to the CWPs. These papers promote international collaboration, describe the status of a truly large-scale sustained ocean observing effort, and collectively help shape a vision for the future. They garner the collective knowledge of the community to evaluate and enhance the efficacy of our global and regional ocean observing networks.

The CWPs summarize key accomplishments in ocean observing, address gaps, and discuss the way forward. They specifically address improved connections between end users and providers of ocean observations, opportunities for integration of observing efforts and applications of information at the global and regional levels. Together, they contribute to a vision for ocean observing opportunities in the coming decade. For example, the importance of ocean observing as the key source of information on natural hazards (e.g., harmful algae and bacteria blooms, tsunamis, storm surges, marine heatwaves, and storms and other extreme weather events), ecosystem health and biodiversity (including shifting distributions of organisms and the increased risk of extinctions), ocean pollution (including acidification, de-oxygenation, and plastics), and sea level change are highlighted by various CWPs. They also identify substantial challenges that need to be overcome as a community, and offer suggestions for solutions. The needs for observations to support ecosystem-based management, marine and weather forecasting, climate predictions and projection, marine safety and navigation, decision support for climate adaptation, deep-ocean exploration, and seafloor mapping, among many other areas, are underscored. These issues are all at the core of a developing blue economy.

The papers address observing systems of various scales, including global ocean (e.g., Argo, GO-SHIP, Volunteer Observing Ships, and an active constellation of satellites), basin-scale (e.g., AtlantOS, Tropical Pacific Observing System 2020, Indian Ocean Observing System, Tropical Atlantic Observing System, Arctic Ocean and Southern Ocean observing systems, and a developing Deep Ocean Observing Strategy), regional (e.g., for boundary currents and inter-ocean exchanges), and coastal. They also address the goal of OceanObs'19 to further refine a governance framework that designates responsibility for product definition, production and timely delivery of fit-for-purpose information to serve user needs at the appropriate scales (global, basin, regional, national).

Taken together, the CWPs represent a call to governmental and non-governmental organizations, industries, scientists and technologists, stewards and citizens to work together to support furthering a coordinated development of the Global Ocean

Observing System (GOOS) to ensure the delivery of information that will benefit human society over the long term. Together, the CWPs and OceanObs'19 will contribute to the development of a vibrant and blue economy that comprises many sectors, that supports policies that sustain development and conservation, and shape the next decade of ocean observing.

The organizers of the OceanObs'19 conference thank the authors that conceived and jointly crafted the CWPs for their tremendous efforts, extensive international collaborations, and community wisdom. The organizers also thank the hundreds of reviewers of the CWPs for their dedication, and the time invested in reviewing the papers. The organizers are also indebted to the entire team of Frontiers in Marine Science for their effort in handling the publications of the CWPs, and the compilation of the eBook.

The articles included in this version of the eBook include CWPs for the OceanObs'19 Research Topic published up to late July. Those published subsequently will be included in an updated version of the eBook.

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REVIEW
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Towards Comprehensive Observing and Modeling Systems for Monitoring and Predicting Regional to Coastal Sea Level

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A major challenge for managing impacts and implementing effective mitigation measures and adaptation strategies for coastal zones affected by future sea level (SL) rise is our limited capacity to predict SL change at the coast on relevant spatial and temporal scales. Predicting coastal SL requires the ability to monitor and simulate a multitude of physical processes affecting SL, from local effects of wind waves and river runoff to remote influences of the large-scale ocean circulation on the coast. Here we assess our current understanding of the causes of coastal SL variability on monthly to multi-decadal timescales, including geodetic, oceanographic and atmospheric aspects of the problem, and review available observing systems informing on coastal SL. We also review the ability of existing models and data assimilation systems to estimate coastal SL variations and of atmosphere-ocean global coupled models and related regional downscaling efforts to project future SL changes. We discuss (1) observational gaps and uncertainties, and priorities for the development of an optimal and integrated coastal SL observing system, (2) strategies for advancing model capabilities in forecasting short-term processes and projecting long-term changes affecting coastal SL, and (3) possible future developments of sea level services enabling better connection of scientists and user communities and facilitating assessment and decision making for adaptation to future coastal SL change.

Keywords: coastal sea level, sea-level trends, coastal ocean modeling, coastal impacts, coastal adaptation, observational gaps, integrated observing system

INTRODUCTION

Coastal zones have large socio-economic and environmental significance to nations worldwide but are exposed to rising SL and increasing extreme SL events (e.g., surges) due to anthropogenic climate change (Seneviratne et al., 2012; Vousdoukas et al., 2018). By 2100, ∼70% of the coastlines are projected to experience a relative SL change within 20% of the global mean SL rise (Church et al., 2013). Future SL extremes will also very likely have a significant increase in occurrence along some coasts (Vitousek et al., 2017; Vousdoukas et al., 2018), but there is in general low confidence in region-specific projections of waves and surges (Church et al., 2013). Similar uncertainties affect efforts to predict coastal SL variability on shorter (seasonal to decadal) periods. Our limited capacity for coastal SL prediction on a range of timescales is a major challenge for understanding impacts, anticipating climate change risks and promoting adaptation efforts on issues such as public safety and relocation, developing and protecting infrastructure, health and sustainability of ecosystem services and blue economies (e.g., Intergovernmental Panel on Climate Change [IPCC], 2014).

While observations from tide gauges, satellite altimetry and less developed methods such as the GNSS reflections are key for monitoring SL, other types of observations as well as model and assimilation systems are also relevant from the broader perspective of coastal SL prediction. For example, bottom pressure and steric height observations, even if mostly in the deep ocean, can shed light on the barotropic or baroclinic nature of SL dynamics. Similarly, information on surface atmospheric winds and pressure, air-sea heat exchanges or river runoff can help to understand and distinguish the influence of local, regional and remote drivers of coastal SL variability. Such knowledge is needed to guide the representation of relevant physical processes and forcing mechanisms in dynamical forecast models or the choice of predictors in statistical methods. In addition, information from all types of observations (not just SL) is essential for defining the initial states of forecast systems.

In this paper we examine the status of observing and modeling systems relevant for both monitoring and predicting coastal SL. (By coastal SL we mean SL at the coast, e.g., as seen by tide gauges, or over contiguous shelf and continental slope regions, in contrast with SL over the deep/open ocean; other terminology used here is consistent with the definitions proposed by Gregory et al., 2019.) Emphasis is on variability at monthly and longer timescales. The main thrusts of the paper have to do with the need to: treat data and model issues in tandem; highlight the importance for coastal SL of many different datasets (besides SL *per se*), physical processes, and timescales; and examine the differences and connections between SL variability in the coastal and open oceans. Section "Causes of Coastal Sea Level Variability" serves to motivate the review of the present status of both observations and model/assimilation systems that follows. For the present observing system status (section "Existing Observing Systems"), we attempt to cover not only SL observations *per se*, but also other ancillary fields, such as waves and temperature, which are important in the interpretation of the coastal SL record. Section "Existing Modeling Systems" deals with the model/assimilation systems used for both coastal analyses/forecasts on relatively short periods, of the type being implemented in operational weather centers around the world, and longer term predictions/projections, typical of efforts under CMIP. Against this background, section "Recommendations for Observing and Modeling Systems" explicitly addresses most relevant needs for improved coastal SL monitoring and predicting capabilities in the future. A related, more specific discussion of the future of SL services, from the perspective

Abbreviations: ANN, artificial neural networks; CMIP, Coupled Model Intercomparison Project; COFS, coastal ocean forecasting system; GLOSS, Global Sea Level Observing System; GNSS, Global Navigation Satellite System; GPS, Global Positioning System; InSAR, interferometric synthetic aperture radar; OBP, ocean bottom pressure; PSMSL, Permanent Service for Mean Sea Level; RCP, representative concentration pathway; SAR, synthetic aperture radar; SL, sea level; SONEL, Système d'Observations du Niveau des Eaux Littorales; UHSLC, University of Hawai'i Sea Level Center; VLM, vertical land motion.

of connecting to end users, is provided in section "Developing Future Sea Level Services."

CAUSES OF COASTAL SEA LEVEL VARIABILITY

In this section, we provide an overview of the many processes that contribute to coastal SL variability, and in particular on the reasons for differences between SL observed at the coast and in the neighboring deep ocean. The discussion is as broad as possible and not specific to any region. Our main focus is on variability on monthly timescales and longer. Therefore, while we discuss high-frequency processes (on timescales of minutes to days, including tides and storm surges), it is primarily to indicate their importance to the longer term record. The subsections below are ordered roughly in terms of increasing timescale of variability.

Higher-Frequency Coast-Ocean Sea Level Differences

Coastal SL variability must in general be larger, and associated with a wider range of timescales than that in the nearby open ocean. For example, at the higher end of the frequencies considered in this paper, tides tend to have larger amplitudes at the coast than in the open ocean, primarily due to shoaling and resonance arising from the depth of coastal waters and shape of coastlines, and they have a richer spectra of high harmonics and shallow water constituents (Pugh and Woodworth, 2014, chapter 5). In addition, a number of important processes that take place near the coast on timescales of minutes, hours or days have magnitudes and/or frequencies that are determined by water depth and the presence of the coastal boundary. These processes include the seiches of harbors, bays and shelves, storm surges, shelf waves, infragravity waves, wave setup and river runoff. **Figure 1** gives a schematic description of some of these processes (for a fuller list and description, see Woodworth et al., 2019).

In fact, some of these higher-frequency processes are important to the discussion of SL variability and change over longer timescales. For example, major periods of storm surge activity in winter will skew the distribution of surges and therefore affect monthly mean SL. Wave setup and run-up provides another example. While run-up is the instantaneous maximum elevation at the moving shoreline, wave setup is the SL averaged typically over many wave groups (tens of minutes). This wave setup is modulated on longer timescales through its dependence on time-varying wave height, period, direction, and "still water" level (Idier et al., 2019). Therefore, setup will inevitably contribute to mean SL variability in some way (e.g., on seasonal and interannual timescales). Consequently, there is a possible "contamination" of existing long term mean SL records by variations in wave setup in the past (IOC, 2016). In addition, the character of the contribution might change again if wind climate or sea ice cover changes in the future, leading to changes in the wave climate (Stopa et al., 2016; Melet et al., 2018). Similar remarks apply to river runoff, which is primarily a high-frequency process (e.g., daily) and yet can contribute to SL variability on seasonal and longer timescales at tide gauges located in or near to major river estuaries (Wijeratne et al., 2008; Piecuch et al., 2018a).

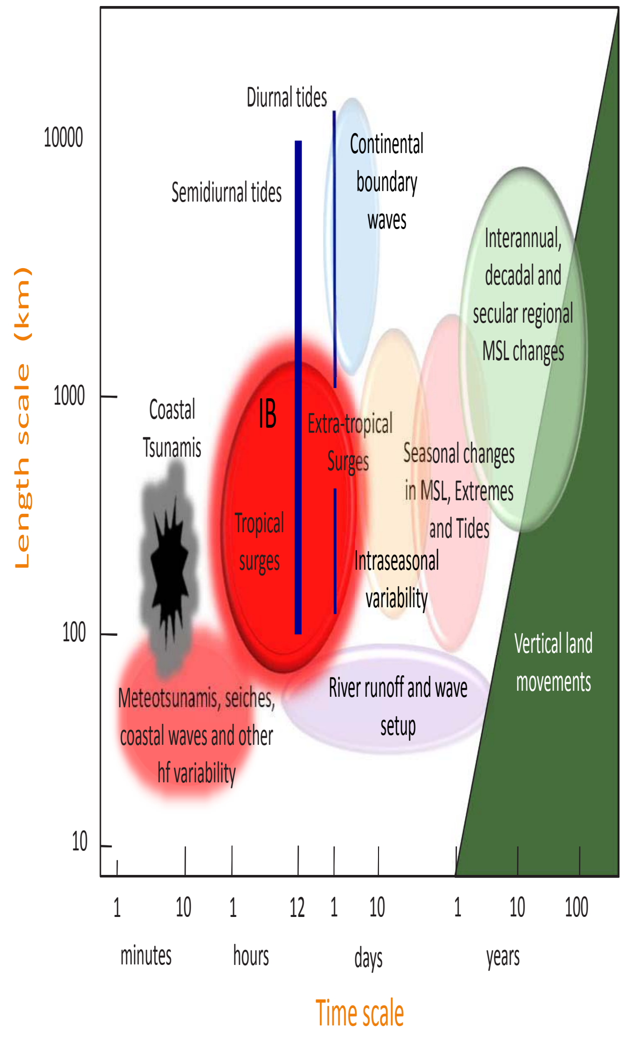

FIGURE 1 | A schematic overview of processes contributing to sea level variability at the coast indicating the space and time scales involved. Woodworth et al. (2019) contains a more complete summary and discussion of each process; Hughes et al. (2019) provides a detailed review of different types of coastal-trapped waves. Very high-frequency processes with timescales less than 1 min (e.g., wind waves, swash) are not included.

Coast-Ocean Comparison on Longer Timescales

Many studies have demonstrated that the differences between open-ocean and coastal SL variability are not confined to the "high-frequency" and "short spatial scale" of the previous section. A well-known example concerns the trapped coastal waves that propagate north and south along the Pacific coasts of the Americas, resulting in similar SL anomalies at all points along the coast (Enfield and Allen, 1980; Pugh and Woodworth, 2014). A similar situation occurs along Australian coasts, where much of the coherence in the north and west is related to El Niño (see references in White et al., 2014), and along the European coasts (e.g., Calafat et al., 2012). Another example is the coherence of variability in sub-surface pressure (akin to inverse-barometer corrected SL) at intra-annual timescales along continental shelf slopes (Hughes and Meredith, 2006).

The accumulation of several decades of satellite altimeter data made it possible to compare SL variability in the open ocean and that at the coast as measured by tide gauges. Differences in variability exist at some locations on monthly to interannual timescales (e.g., Vinogradov and Ponte, 2011). Such differences are of particular interest where they reflect the dynamics of the nearby ocean circulation, and especially of western boundary currents (e.g., Yin and Goddard, 2013; Sasaki et al., 2014; McCarthy et al., 2015). Further studies are needed (e.g., using re-tracked coastal altimetry products) to identify the relative contributions of measurement issues (e.g., contamination of the altimeter footprint, uncertainties in correction algorithms) and representation errors (e.g., coastally trapped circulations) to the observed differences between tide gauge and altimetry data.

The performance of ocean models (Calafat et al., 2014; Chepurin et al., 2014) and coupled climate models (Becker et al., 2016; Meyssignac et al., 2017b) in reproducing historical coastal SL changes observed by tide gauges is varied, with the models performing well for some regions and timescales, but poorly for others. Consequently, better understanding of model-data discrepancies, and in particular the faithfulness of models in simulating the processes mediating the relationship between coastal SL and large-scale ocean circulation, will be required to improve and add confidence to projections of future coastal SL change (see section "Existing Modeling Systems").

Importance to Coastal SL of Climate Modes and Ocean Dynamics

The influence of the major modes of climate variability (e.g., El Niño-Southern Oscillation, North Atlantic Oscillation, Indian Ocean Dipole, Pacific Decadal Oscillation) can be seen in spatial patterns of SL variability both at the coast and in the ocean interior, and in both coastal mean and extreme SL (e.g., Menéndez and Woodworth, 2010; Barnard et al., 2015). These modes have basin-wide influence on SL at interannual-to-decadal timescales and have large impacts on coastal oceans through local wind forcing associated with climate modes and also remote influence from the ocean interior. For instance, interannual-to-decadal surface wind anomalies associated with El Niño and Indian Ocean Dipole induce eastward propagating oceanic equatorial Kelvin waves. Upon arriving at the eastern boundary, part of the energy propagates poleward as coastally trapped waves, affecting SL in a long distance along the coastlines of the eastern Pacific (e.g., Chelton and Enfield, 1986) and eastern Indian Ocean (e.g., Han et al., 2017, 2018). Eastern boundary SL is also affected at interannual to decadal timescales by variability in longshore winds associated with extratropical atmospheric centers of action related to climate modes (Calafat et al., 2013; Thompson et al., 2014).

At the western boundary, in regions where the shelf is broad (e.g., Mid-Atlantic Bight), circulations over the shelf can be distinct from the open ocean, large-scale (greater than Rossby radius) circulation (Brink, 1998). Open ocean currents flow along the isobaths, setting a barrier for cross-isobath flows and thus constrain the influence of remote forcing from the open ocean on coastal SL. The generation of cross-isobath currents must be through ageostrophic processes (e.g., external surface forcing, non-linearity, friction). By including variable rotation effects, however, some Rossby wave energy can cross isobaths and arrive at the western ocean boundary (Yang et al., 2013). Indeed, a coastal sea level signal which is derived from open ocean dynamics has been observed but with significantly reduced amplitude at the coast and a shift toward the equator (Higginson et al., 2015). Part of this effect has been explained theoretically, for an ocean with vertical sidewalls (Minobe et al., 2017). The extension to include a continental slope shows that the same kind of spatial shift and reduction in amplitude still occurs, but is enhanced to a degree that depends sensitively on resolution and friction (Wise et al., 2018). This effect can be understood as an influence of coastal-trapped waves on the propagation of signals between open-ocean and coastal regions; see Hughes et al. (2019) for a review.

The SL and temperature variability associated with climate modes can result in coastal impacts, such as flooding or coral bleaching around coastlines and low-lying coral islands (e.g., Dunne et al., 2012; Ezer and Atkinson, 2014; Barnard et al., 2015; Ampou et al., 2017; Schramek et al., 2018). Interpretation of correlations between climate modes and SL should be made carefully, as climate modes reflect statistical summaries of multivariate behavior in the climate system. They are useful constructs though not themselves primary drivers of SL change (e.g., Kenigson et al., 2018). Rather, such correlations often indicate a direct forcing of the ocean by the atmosphere, locally or remotely, by means of such mechanisms as the inverted barometer effect, storm surge, wind setup, Ekman transport, Rossby waves, or Sverdrup balance (Andres et al., 2013; Landerer and Volkov, 2013; Thompson and Mitchum, 2014; Piecuch et al., 2016; Calafat et al., 2018). It has also been proposed (e.g., along the Eastern United States) that coastal SL is causally linked to other components of the variable and changing climate system, such as subpolar ocean heat storage (Frederikse et al., 2017), the changing mass of the Greenland Ice Sheet (e.g., Davis and Vinogradova, 2017), changes to the Gulf Stream (Ezer et al., 2013) and Atlantic Meridional Overturning Circulation (Yin et al., 2009; Yin and Goddard, 2013), depending on timescale.

Global eddy-resolving models have revealed the strength of the intrinsic ocean variability, which spontaneously emerges from oceanic non-linearities without atmospheric variability or any air-sea coupling (Penduff et al., 2011; Sérazin et al., 2015, 2018). These signals have a chaotic character (i.e., their phase is random and not set by the atmosphere; Penduff et al., 2018), impact most oceanic fields such as SL, ocean heat content, overturning circulation (e.g., Zanna et al., 2018), can reach the scale of gyres and multiple decades, and may blur the detection of regional SL trends over periods of 30 years (Sérazin et al., 2016), and in particular over the altimetric period (Llovel et al., 2018). This phenomenon has mostly been studied in the open ocean, but ongoing research shows that it impacts the 1993–2015 trends of SL in certain coastal regions (e.g., Yellow Sea, Sea of Japan, Patagonian plateau), raising new issues for the understanding, detection and attribution of coastal SL change.

This stochastic variability is most strongly manifested in the mesoscale, which dominates SL variability in much of the ocean. However, the mesoscale is strongly suppressed by long continental slopes, leading to a decoupling between open ocean and shelf sea variability, especially in high latitudes and western boundaries (Hughes and Williams, 2010; Bingham and Hughes, 2012; Hughes et al., 2018, 2019). The result is that open ocean-shelf coupling only tends to occur on larger scales, though there is still a significant stochastic part derived from the integrated effect of the mesoscale. An exceptional example is the Caribbean Sea, where a basin mode (the Rossby Whistle) is excited by the mesoscale and has a strong influence on coastal SL at 120-day period (Hughes et al., 2016). Similarly, the short circumference of continental slopes around oceanic islands allows for the ready influence of mesoscale open ocean variability on their shorelines (Mitchum, 1995; Firing and Merrifield, 2004; Williams and Hughes, 2013).

Secular Coast-Ocean Differences

An obvious difference between coastal SL as seen by a tide gauge and open ocean SL as measured by an altimeter, which manifests itself primarily in the discussion of long-term SL trends, is that the former is made relative to land levels at the tide gauge stations, whereas the latter are referenced to the geocenter. Differences between the two SL measurements are rendered by VLMs, which can arise from a wide variety of processes (glacial isostatic adjustment, sediment compaction, tectonics, groundwater pumping, dam building) operating over a broad range of space and time scales (Emery and Aubrey, 1991; Engelhart and Horton, 2012; Kemp et al., 2014; Karegar et al., 2016; Johnson et al., 2018). Related bathymetric changes can also influence many coastal processes. Modern geodetic techniques are required to place the tide gauge data into the same geocentric reference frame as for the altimeter data, and to monitor VLM at the gauge sites (IOC, 2016; Wöppelmann and Marcos, 2016) and to understand as well as possible the evolution of coastal zones (Cazenave et al., 2017). Application of geodetic approaches in SL studies is limited currently by the spatial sparseness of the data, the temporal shortness of the records, and difficulties associated with realizing the terrestrial reference frame (cf. section "Sea Level Observations").

Sea Level Change Impacts at the Coast

Major differences between ocean and coastal SL occur through processes that depend upon water depth, such as storm surges that lead to extreme SLs. A particular concern for coastal managers has to do with the extreme SLs and associated coastal inundation and flooding, that are occurring increasingly often (e.g., Sweet and Park, 2014). Extreme SL arises from combinations of high astronomical tides and other processes, in particular storm surges and waves (Merrifield et al., 2013). Changes in extremes have been found to be determined to a great extent by changes in mean SL, although not exclusively so (e.g., Marcos and Woodworth, 2017; Vousdoukas et al., 2018). These studies often make use of tide gauge data with its traditional hourly sampling of SL. Such sampling ignores the high-frequency part of the SL variability spectrum (timescale $<$ 2 h, which includes most seiches), which should be accounted for, at least on a statistical basis, in future studies of extremes (Vilibić and Šepić, 2017). Also global scale studies of the impacts of sea level extremes do not include high-frequency wave-related processes such as swash.

However, the coast can also be impacted by changes in mean SL, which is known to be rising globally as a consequence of climate change (Church et al., 2013). The first years of altimeter data suggested that SL might be rising at a greater rate near to the coast than in the nearby deeper ocean (Holgate and Woodworth, 2004) although such a difference was not considered significant by others (White et al., 2005; Prandi et al., 2009). Nevertheless, as the depth of coastal waters increases in the future, many of the processes mentioned above will be modified: e.g., tidal wavelengths will increase and tidal patterns over the continental shelves will change (e.g., Idier et al., 2017); storm surge gradients and magnitudes will reduce (because of their dependence on 1/depth); changes to tides and surges imply changes to SL extremes; ocean waves will break closer to the coast, with associated changes in wave setup and run-up (Chini et al., 2010) and amplified potential flooding impacts (Arns et al., 2017). Many of these factors, as well as related morphological changes not discussed here, can be expected to interact with each other (Idier et al., 2019).

Summary: A Complexity of Coastal Processes

The nature of coastal SL variations is complex and multifaceted, reflecting the influence of a multitude of Earth system processes acting on timescales from seconds to centuries and on spatial scales from local to global. Successful efforts to monitor and predict coastal SL must acknowledge this complexity and deal with the challenges of observing many different variables, from local and remote winds and air pressure to river runoff and bathymetry, and modeling a wide range of processes, from wind waves, tides and large-scale climate modes, to compaction, sedimentation and tectonics affecting VLM (**Figure 1**).

EXISTING OBSERVING SYSTEMS

Sea Level Observations

Tide gauges (Holgate et al., 2013) and satellite altimetry (Vignudelli et al., 2011; Cipollini et al., 2017a,b) are both important sources of SL information in the coastal zone. This section focuses on tide gauge observations and related systems. Benveniste et al. (2019) provide a discussion of coastal altimetry, including the complementarity between altimetry and tide gauge observations.

Coastal tide gauges measure point-wise water levels, from which mean and extreme SL can be estimated. The longest tide gauge records date back to the 18th century, although it was only during the mid-20th century that the number of instruments increased significantly, given their applications not

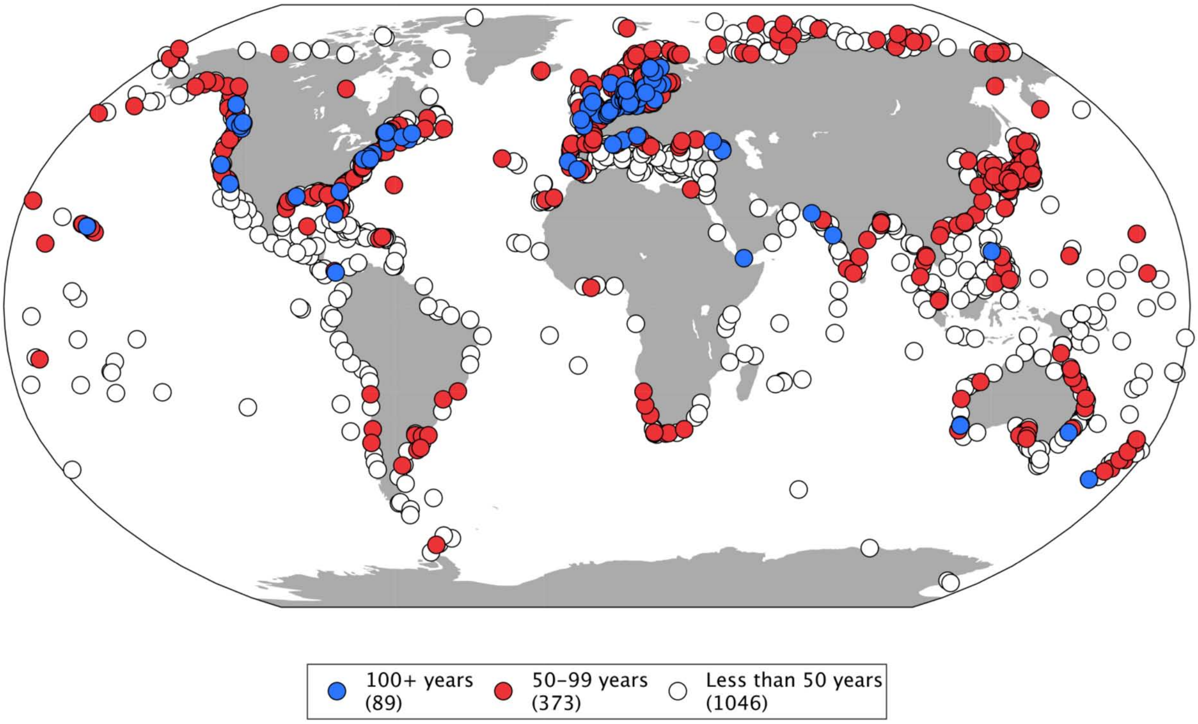

FIGURE 2 | Tide gauge monthly sea level records available at PSMSL. In color, time series longer than 50 (red) and 100 (blue) years. Number of stations in each category is given in parentheses.

only for scientific purposes but also for maritime navigation, harbor operations, and hazard forecasting. Currently, most of the world coastlines are monitored by tide gauges (**Figure 2**), generally operated by national and sub-national agencies. Many of these tide gauge records are compiled and freely distributed by international databases. Among these, the PSMSL[1], hosted by the National Oceanography Centre in Liverpool, is the largest data bank of long-term monthly mean SL records for more than 2000 tide gauge stations (Holgate et al., 2013; see **Figure 2**). Other data portals provide higher frequency (hourly and higher) SL observations required for the study of tides and extreme SL and/or real time measurements needed for operational services or tsunami monitoring and warning systems; this is the case of the UHSLC[2], the European Copernicus Marine Environment Monitoring Service[3] or the Flanders Marine Institute[4] that hosts the GLOSS monitoring facility for real time data. The Global Extreme Sea Level Analysis initiative[5] extends the UHSLC high frequency SL data set, unifying and assembling delayed-mode observations compiled from national and sub-national agencies, and presently provides the most complete collection of high-frequency SL observations, with 1355 tide gauge records, of which 575 are longer than 20 years (Woodworth et al., 2017a).

Despite the extensive present-day tide gauge network, only a fraction of the SL records spans a multi-decadal period necessary for climate studies. In the PSMSL data base, for example, only 270 (89) tide gauge records out of 1508 are longer than 60 (100) years – the minimum length considered by Douglas (1991) for the computation of linear trends – and only 632 overlap with altimetric observations during at least 15 years. Moreover, the longest tide gauge records tend to be located mostly in Europe and North America, while few are found in the Southern Hemisphere. This uneven spatial and temporal tide gauge distribution is one of the main factors that challenge the quantification and understanding of contemporary SL rise at regional and global scales (Jevrejeva et al., 2014; Dangendorf et al., 2017).

One of the tools to overcome the scarcity of coastal SL observations in the early 20th century and before, consists in the recovery and quality control of historical archived SL measurements, also referred to as data archeology (Bradshaw et al., 2015). These efforts have so far extended records from the PSMSL data set (Hogarth, 2014) and have successfully recovered new SL information at sites as remote as the Kerguelen Island (Testut et al., 2006) or the Falklands (Woodworth et al., 2010) and as far back in time as the 19th century (Marcos et al., 2011; Talke et al., 2014; Wöppelmann et al., 2014).

Tide gauges measure SL with respect to the land upon which they are grounded. Thus, to be useful for climate studies, tide gauge SL records must refer to a fixed datum, known as tide gauge benchmark, that ensures their consistency and continuity.

[1]https://www.psmsl.org
[2]https://uhslc.soest.hawaii.edu/
[3]http://marine.copernicus.eu/
[4]http://www.vliz.be/en
[5]https://www.gesla.org

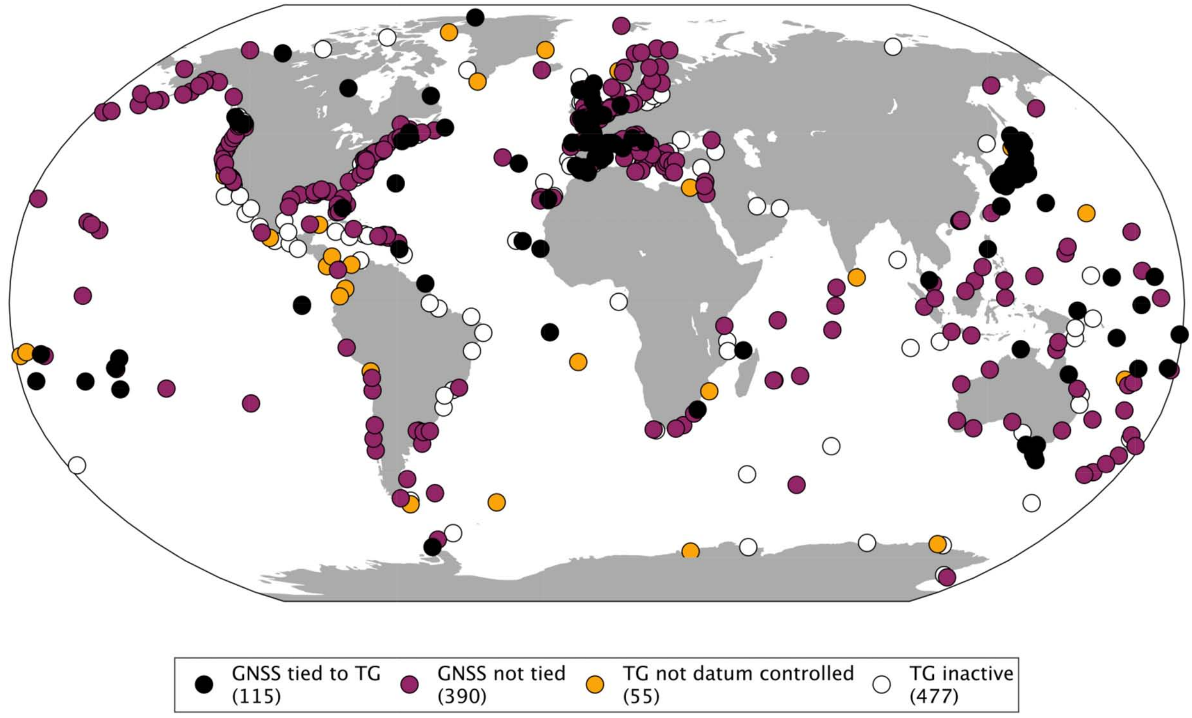

FIGURE 3 | Tide gauges and collocated GPS. Number of stations in each category is given in parentheses.

Neither the land nor the SL are constant surfaces, so precise estimates of the VLM of the tide gauge benchmark are necessary in order to disentangle the climate contribution to SL change in tide gauge records. Presently, GNSS, with its most well-known component being the GPS, provide the most accurate way to estimate the VLM at the tide gauge benchmarks (Wöppelmann and Marcos, 2016). One major underlying assumption of the GPS-derived VLM at tide gauges is that the trend estimated from the shorter length of the GPS series is representative of the longer period covered by the tide gauge. When this is the case, GPS VLM reaches an accuracy one order of magnitude better than SL trends (Wöppelmann and Marcos, 2016). Another limitation is the accuracy of the reference frame on which the GPS velocities rely (Santamaría-Gómez et al., 2017). Global GPS velocity fields are routinely computed and distributed by different research institutions (International GNSS Service, Jet Propulsion Laboratory, University of Nevada, University of La Rochelle). Among these, only the French SONEL[6] data center, hosted at the University of La Rochelle, provides GPS observations and velocity estimates focused on tide gauge stations, where possible providing links to PSMSL, to form an integrated observing system within the GLOSS program. **Figure 3** maps the global tide gauge stations that are datum controlled and/or tied to a nearby GPS station for which VLM estimates exist. The number of tide gauge stations with co-located GPS is still a small fraction of the total network (e.g., only 394 stations in PSMSL are within a 10 km distance from a GPS station and, among these, only for 102 stations the leveling information between the two datums is available), despite recurrent GLOSS recommendations in this respect. The inability to account for VLM at tide gauges and therefore to separate the non-climate contribution of land from observed coastal SL, is another factor hampering the understanding of past SL rise.

As noted above, the continued deployment of GNSS receivers near or at tide gauges is critical. In this regard, a point also worth stressing concerns the actual placement of these systems: it is most useful if they are deployed so as to have an open view of the sea, thus allowing the measurement of both direct and reflected radio waves. The GNSS-reflectometry technique has proven that coastal GNSS stations can be used to supplement conventional tide gauges. **Figure 4** compares 1 year-long time series of daily mean SL, produced from GPS reflections and from a standard acoustic tide gauge, with root-mean-square differences at the level of 2 cm (Larson et al., 2017). If installed in the vicinity of a tide gauge, GNSS receivers can provide a valuable backup as well as the direct tie between the tide gauge zero-point and the terrestrial reference frame (Santamaría-Gómez and Watson, 2017). There is no additional cost for developing new instrumentation, since standard geodetic-quality receivers can be used. However, data treatment is more complex than for a tide gauge and high frequency (daily) measurements are noisier in the case of a GNSS receiver.

Ancillary Observations

The interpretation of coastal SL measurements benefits from complementary information provided by other ancillary

[6]http://www.sonel.org

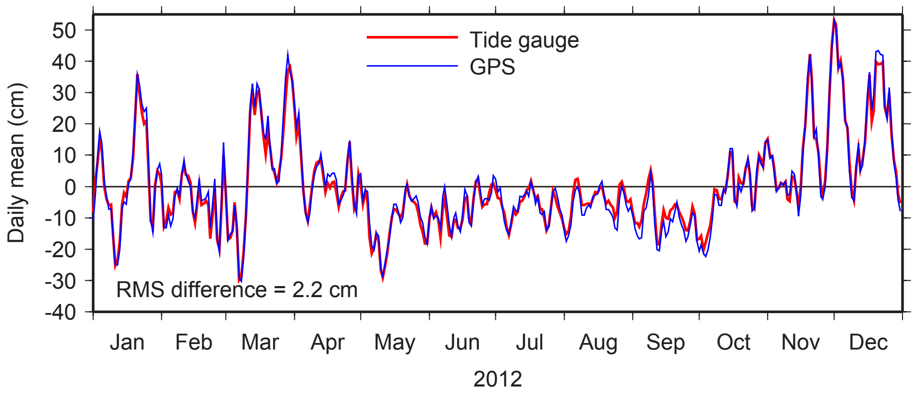

FIGURE 4 | Daily mean sea level during 2012 at Friday Harbor, Washington, United States, in the Strait of Juan de Fuca. Red line is daily means deduced from the Friday Harbor tide gauge, operated by NOAA; blue line is daily means determined by analysis of GPS reflected signals at station SC02, sited 300 m from the tide gauge. Adapted from Larson et al. (2017), who give further comparisons over a 10-year period, including comparisons of tidal constants.

observing systems focusing on various SL driving mechanisms and contributors. Among the components that impact coastal SL, wind-waves have a dominant role along many of the world coastlines acting at different timescales: from wave setup that modifies mean SL at the coast with timescales of a few hours, up to swash lasting only a few seconds. In the deep ocean, wind-waves are routinely monitored by *in situ* moored buoys, ship observations (Gulev et al., 2003) and satellite altimetry (Queffeulou, 2013). The offshore waves are strongly transformed in shallow waters owing to changing bathymetries and ocean bottom and thus display also large spatial variability even at small scales (∼10–100 m) along the coastal zone. Given the wide range of spatio-temporal scales, observations of wind-waves at the coast are generally recorded only at specific sites and target particular processes. Coastal wind-wave monitoring platforms include coastal pressure and wave-gauge deployments for near-shore waves, video monitoring techniques for shoreline positions (e.g., Holman and Stanley, 2007) and *in situ* field surveys for topo-bathymetries. Despite the impact that the topography and bathymetry of the surf zone have on wind-waves, lack of their routine measurement is currently one of the major gaps that limit the knowledge of wave transformations when approaching the coastal zone, especially in places with active seabed dynamics. This lack of information has also an effect on the ability of numerical models to predict both the coastal wave properties and the morphodynamical changes induced by their action. Given the impact of wind-waves on coastal SL, the inability to systematically observe coastal waves is a major knowledge gap.

Coastal SL is partly driven by changes in the deep ocean, where SL variations are largely due to water density (steric) changes (Meyssignac et al., 2017a). These signals are transferred to the coasts through a variety of mechanisms that depend on the open ocean circulation characteristics and on the physical processes taking place over the continental slope (e.g., Bingham and Hughes, 2012; Minobe et al., 2017; Calafat et al., 2018; Wise et al., 2018; see section "Causes of Coastal Sea Level Variability"). Therefore, observations of temperature and salinity in the open ocean, like those provided by the global Argo program, are also relevant to coastal SL. Unlike the deep ocean, density measurements are scarce over continental shelves, in enclosed or semi-enclosed basins and in the coastal zone. These measurements are generally obtained from dedicated field experiments or local/regional observing systems (e.g., Heslop et al., 2012; Rudnick et al., 2017) and are focused in areas of particular oceanographic interest (e.g., strong ocean currents, intense atmosphere-ocean interactions, fisheries). The hydrographic data scarcity in the shallow regions is a major hurdle to understand the small scale coastal dynamics and their impact on SL. On the other hand, sea surface temperature has shown covariability with SL along some coastal zones at interannual to decadal time scales, which is related to the fact that both are partly driven by air-sea heat fluxes (Meyssignac et al., 2017a). High-resolution, remote-sensed sea surface temperature can thus provide useful spatially detailed information for interpretation of SL features over the coastal zone (Marcos et al., 2019).

Ocean bottom pressure is another factor related to SL variability, especially over the continental shelves (e.g., Marcos and Tsimplis, 2007; Calafat et al., 2013; Piecuch and Ponte, 2015). Currently, satellite gravimetry, starting in 2002 with the launch of the GRACE mission, is the main source of observations of OBP changes over the deep ocean that allows separating the mass component from observed SL (Chambers et al., 2004). Available GRACE observations have relatively coarse resolution (∼300 km) and can be contaminated by leakage from larger land water fluctuations, but recent work by Piecuch et al. (2018b) highlights their usefulness in understanding the tide gauge records. Alternatively, OBP observations are also provided by *in situ* moored buoys. The largest network of OBP recorders is maintained and its data distributed by NOAA through the National Data Buoy Center website[7]. These OBP sensors display an uneven spatial distribution, as they are concentrated in areas of oceanographic interest or are part of tsunami warning systems,

[7] http://www.ndbc.noaa.gov

with most of them located in the deep ocean. OBP recorders are useful to quantify short-term ocean mass changes (Hughes et al., 2012), but they cannot be used to monitor long-term changes due to large internal drifts (Polster et al., 2009). The large-scale coherence of OBP signals along the continental shelves (Hughes and Meredith, 2006) suggests that they could be monitored with a relatively small network of *in situ* instruments, to overcome the currently limited set of OBP observations in coastal regions. However, this observational system does not exist so far at least on the global scale.

Monitoring and modeling of the main drivers of coastal SL variability (surface atmospheric winds and pressure, precipitation, evaporation, freshwater input at the coast from rivers and other sources), as well as other SL-related variables, is of course also essential. New observations have recently become available from remote sensing of wind speed, waves, SL and currents using X-band and high-frequency radar, acoustic Doppler current profilers, lidar, and Ku-band and Ka-band pulse-limited and delay Doppler radar altimetry, which promise high-quality space observations in the coastal zones (Fenoglio-Marc et al., 2015; Cipollini et al., 2017a,b). All these data are expected to improve forecasting model systems (Le Traon et al., 2015; Verrier et al., 2018). Observations relevant to the coastal forcing fields and other oceanic and atmospheric variables are discussed in a broader context by Ardhuin et al. (2019), Benveniste et al. (2019), and Cronin et al. (2019), among others.

EXISTING MODELING SYSTEMS

Modeling systems are essential for SL forecasts and projections. This section reviews the status of both regional model/data assimilation systems producing mostly short-term forecasts (order of days to weeks) and global coupled models used in long term climate projections. The discussion of the short-term forecast systems serves to highlight many issues of potential relevance (e.g., resolution, timescale interactions, data assimilation) for coastal SL prediction at the longer timescales as well.

Coastal Models and Sea Level Forecasts

In a very broad sense, a SL forecast can rely on three different approaches: (i) the use of realistic numerical models to resolve the processes that govern the ocean dynamics; (ii) the use of observations, which combined with statistical techniques are used to identify space and time patterns and extrapolate them into the future (e.g., linear regressions, ANN), and (iii) the hybrid approach, which combines the first two in a wide variety of ways. For instance, a given numerical model forecast can incorporate data assimilation to reduce the forecast errors and/or use an ensemble of forecasts to present the predictions with confidence intervals.

Kourafalou et al. (2015a,b) and De Mey-Frémaux et al. (2019) define a COFS as a combination of a comprehensive observational network and an appropriate modeling system that ensures the ongoing monitoring of changes in the coastal ocean and supports forecasting activities that can deliver useful and reliable ocean services. The Coastal Ocean and Shelf Seas Task Team within the Global Ocean Data Assimilation Experiment OceanView[8] is an example of an effort that fosters the international coordination of these activities.

An adequate COFS should be able to monitor, predict and disseminate information about the coastal ocean state covering a wide range of coastal processes. These include: tides, storm surges, coastal-trapped waves, surface and internal waves, river plumes and estuarine processes, shelf dynamics, slope currents and shelf break exchanges, fronts, upwelling/downwelling and mesoscale and sub-mesoscale eddies. These variations occur over a wide range of time and space scales and have magnitudes of order 10^{-1}–10^{1} m (**Figure 1**).

The numerical models that integrate the primitive equations for solving the physical processes in a given COFS can vary in terms of complexity, from the more simplistic 2D shallow water equation models to the state-of-the-art 3D community models, such as the Regional Ocean Modeling System (ROMS[9], Shchepetkin and McWilliams, 2005) and the Hybrid Coordinate Ocean Model (HYCOM[10], Chassignet et al., 2003, 2007). While ROMS and HYCOM are based on a structured grid mesh, there is also a variety of models that use unstructured grids to facilitate an increase of resolution in areas of shallow or complex bathymetry. An example of such model is the Delft3D Flexible Mesh Suite[11] or the Semi-implicit Cross-scale Hydroscience Integrated System Model (SCHISM)[12]. A table with some examples of COFS organized by region, maintained at https://www.godae-oceanview.org/science/task-teams/coastal-ocean-and-shelf-seas-tt/coss-tt-system-information-table/, illustrates the wide variety of models that can be used for this purpose. See also Fox-Kemper et al. (2019), which focuses on advances in ocean models and modeling.

Considering that the coastal ocean is both locally and remotely forced (e.g., Simpson and Sharples, 2012), a common adopted strategy is the use of a downscaling approach where remote forcing (e.g., large-scale currents and associated thermohaline gradients, tidal currents, swell) are incorporated in the COFS via initial and boundary conditions derived from coarser Ocean Forecasting Systems (see Tonani et al., 2015 for a worldwide list of such systems). The COFS forcing functions should represent all important shelf and coastal processes that influence SL, such as air-sea interaction, which close to coastal regions is affected by various time and space scales, and land-sea interaction, via coastal runoff, which governs buoyancy-driven currents that are further modified by the wind-driven circulation and shelf topography. An ideal COFS should include a robust data assimilation scheme capable of handling intrinsic anisotropy of the coastal region (Barth et al., 2007; Li et al., 2008; Tandeo et al., 2014; Stanev et al., 2016).

Several factors account for COFS uncertainties: imperfect atmospheric forcing fields; errors in boundary conditions

[8]https://www.godae-oceanview.org/
[9]http://myroms.org
[10]http://hycom.org
[11]https://www.deltares.nl/en/software/delft3d-flexible-mesh-suite/
[12]http://ccrm.vims.edu/schismweb

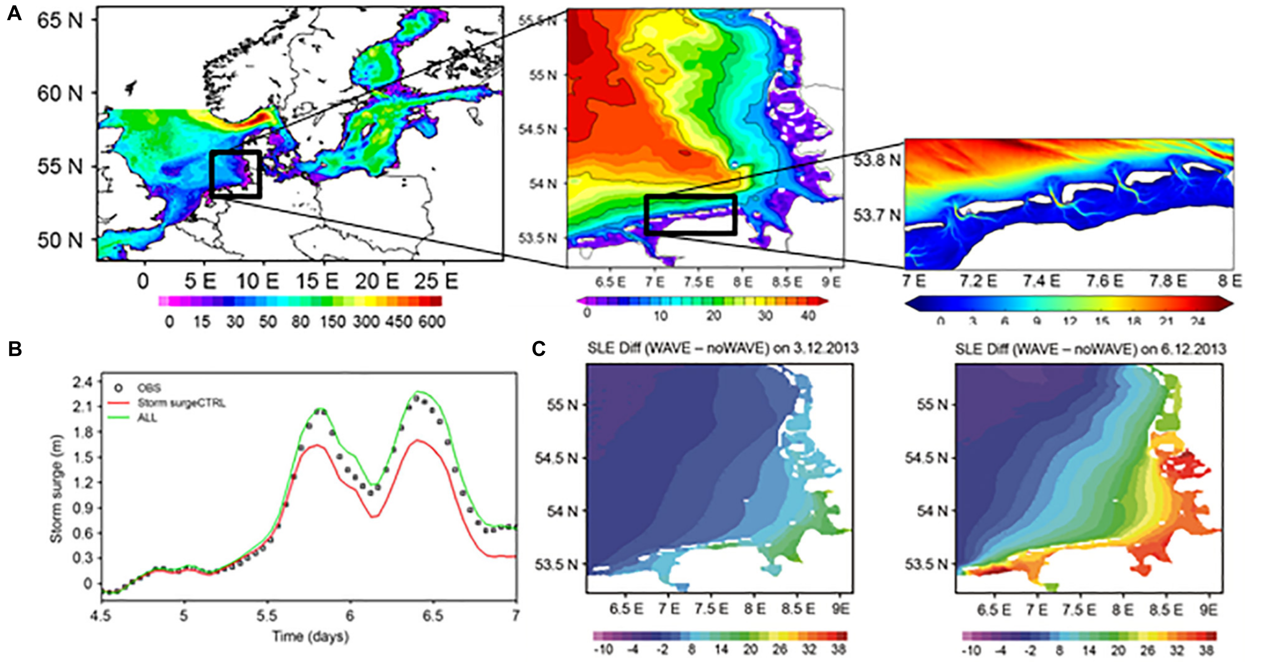

FIGURE 5 | (A) Bathymetry of the nested grid model domains for the North Sea (left pattern), German Bight (middle pattern), and the east Wadden Sea (right pattern). The spatial resolution is 3 nm, 1 km, and 200 m, respectively. **(B)** Observed (black squares) against computed storm surges for the circulation model only (red line) and the coupled wave-circulation model (green line) during storm Xavier at station Helgoland. The *X*-axis corresponds to the time in days from December 1, 2013. **(C)** Sea level elevation (SLE) difference (cm) between the coupled wave–circulation model and circulation-only model for the German Bight on December 3, 2013 at 01:00 UTC (left) and during the storm Xavier on December 6, 2013 at 01:00 UTC (right). Adapted with permission from Staneva et al. (2016a, 2017).

propagating into the finer scale model domain; bathymetric errors; lack of horizontal and vertical resolution and numerical noise and bias; errors in parameterizations of atmosphere-ocean interactions and sub-grid turbulence; intrinsic limited model predictability (strong non-linearity), among many others. To improve prediction skill, data assimilation is used as a way of combining the results of numerical simulations with observations, so that an optimized representation of reality can be achieved. For this purpose, a range of algorithms is used in COFS such as the Optimal Interpolation (OI), the three-dimensional variational (3DVAR), the Ensemble Kalman Filter (EnKF), and the four-dimensional variational (4DVAR) data assimilation methods (Martin et al., 2015). The computational time involved in data assimilation can vary considerably based on the adopted algorithm and is also dependent on the chosen data assimilation cycle as well as the parameters that are assimilated in the COFS.

In analogy to the Earth System Models used in SL projections, COFS can also be coupled in many ways, such as atmosphere-to-ocean, wave-to-ocean and hydrology-to-ocean. As they are generally nested in regional and global models, COFS are particularly suited for coastal-offshore interactions and shelf break processes (provided that the nesting boundary is adequately offshore). An example of how coupling and a multi-nesting, downscaling approach can improve COFS quality is given by Staneva et al. (2016a). They employed a coupled wave-to-ocean model and three grids (horizontal resolutions of 3 nm, 1 km, and 200 m, **Figure 5**) to build a COFS capable of resolving non-linear feedback between strong currents and wind waves in coastal areas of the German Bight. Improved skill is demonstrated in the predicted SL and circulation during storm conditions when using a coupled wave-circulation model system (Staneva et al., 2017). During storm events, the ocean stress was significantly enhanced by the wind-wave interaction, leading to an increase in the estimated storm surge (compared to the ocean model only integration) and values closer to the observed water level (**Figure 5B**). The effects of the waves are more pronounced in the coastal area, where an increase in SL is observed (Staneva et al., 2016b). While maximum differences reached values of 10–15 cm during normal conditions, differences higher than 30 cm were found during the storm, along the whole German coast, exceeding half a meter in specific locations (**Figure 5C**).

Extreme events potentially associated with land falling hurricanes or extra-tropical storms can cause severe damage in coastal communities. In the US, operational guidance from storm surge and inundation models are used to inform emergency managers on whether or not to evacuate coastal regions ahead of storm events (Feyen et al., 2013). Kerr et al. (2013) investigated model response sensitivities to mesh resolution, topographical details, bottom friction formulations, the interaction of wind waves and circulation, and non-linear advection on tidal and hurricane surge and wave processes at the basin, shelf, wetland, and coastal channel scales within the Gulf of Mexico. **Figure 6** presents their results based on two configurations of an

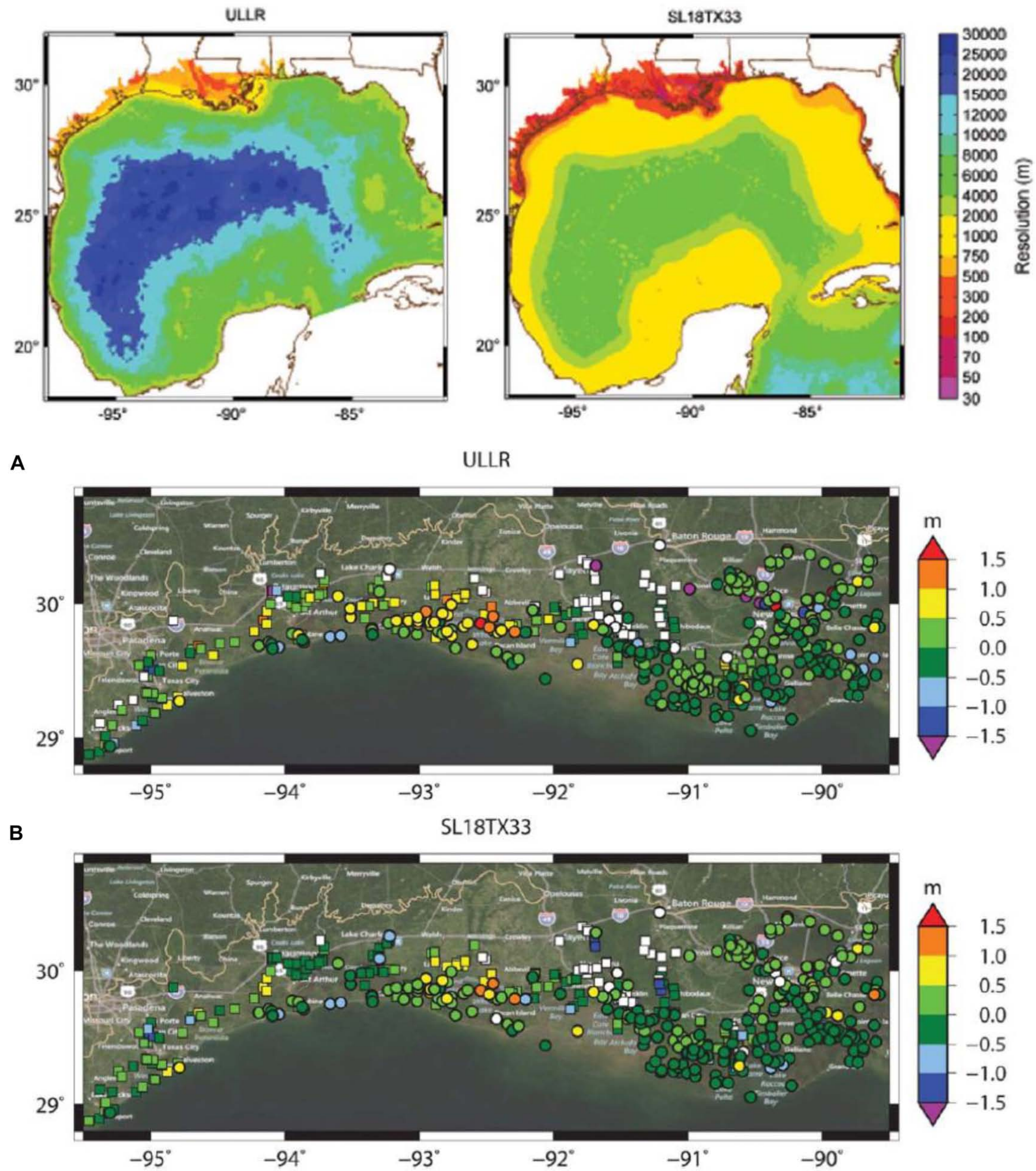

FIGURE 6 | Top panels represent grid resolution in meters of two different model configurations for the Gulf of Mexico (lower resolution labeled ULLR; higher resolution labeled SL18TX33). Locations of Hurricane Ike peak water levels along the northwest Gulf Coast simulated by **(A)** ULLR and **(B)** SL18TX33 (circles), and measured by hydrographs (squares). The points are color-coded to show the errors between measured and modeled peak water levels. Green points indicate matches within 0.5 m and white points indicate locations that were never wetted by the model. Adapted with permission from Kerr et al. (2013).

unstructured-mesh, coupled wind-wave and circulation (shallow-water) modeling system, in a hindcast of Hurricane Ike that passed over the U.S. Gulf of Mexico coast in 2008. They show that the improved resolution is an important factor in predicting SL values much closer to those measured by the hydrographs.

The influence of strong boundary currents can also be important contributors for unusual SL changes. Usui et al. (2015) describe a case study to indicate the importance of a robust data assimilation scheme to accurately forecast an unusual tide event that occurred in September 2011 and caused flooding at several coastal areas south of Japan. Sea level rises on the order of 30 cm were observed at three tide-gauge stations and were associated with the passage of coastal trapped waves induced by a short-term fluctuation of the Kuroshio Current around (34°N, 140°E).

Probabilistic models have also been used alone or in conjunction with deterministic models for SL forecasts in various regions. Sztobryn (2003) used an ANN to forecast SL changes during a storm surge in a tideless region of the Baltic Sea where SL variations are pressure- and wind-driven. Bajo and Umgiesser (2010) used a combination of a hydrodynamic model and an ANN to improve the prediction of surges near Venice, in the Mediterranean Sea. French et al. (2017) combine ANN with computational hydrodynamics for tide surge inundation at estuarine ports in the United Kingdom to show that short-term forecast of extreme SL can achieve an accuracy that is comparable or better than the United Kingdom national tide surge model.

Climate Models and Sea Level Projections

Dynamic changes of the ocean circulation are the major source of regional SL variability in the open ocean (Yin, 2012; Church et al., 2013; Slangen et al., 2014; Jackson and Jevrejeva, 2016). Estimates of future dynamic SL variability, accounting for all contributions to regional SL change, are needed for understanding the magnitude, spatial patterns, and quality of regional to coastal SL projections.

Based on the CMIP5 ensemble, changes in interannual sea level variability from the historical modeled time frame 1951–2005 to the future modeled time frame 2081–2100 are mostly within ±10% for the RCP4.5 scenario, outside of the high-latitude Arctic region (Church et al., 2013). For decadal variability, Hu and Bates (2018) report that changes for period 2081–2100 are more consistently positive, and larger, over more of the ocean, and more so for RCP8.5 than RCP4.5, though this study uses a single model with a large ensemble.

Sources of inter-model uncertainty can be numerous, and include: model response to surface heat, freshwater, and wind forcing (Saenko et al., 2015; Gregory et al., 2016; Huber and Zanna, 2017); air-sea flux uncertainties, including fresh water fluxes (Stammer et al., 2011; Huber and Zanna, 2017; Zanna et al., 2018); different climate sensitivities (Melet and Meyssignac, 2015) and initial ocean states (Hu et al., 2017). Such intermodel uncertainty of regional SL change by 2090 can account for around 70% of total model uncertainty, including scenario uncertainty, meaning differences due to various RCP forcings, and the internal climate variability within individual models can account for approximately 5% of the total uncertainty for regional SL changes out to 2090 (Little et al., 2015). However, with these model uncertainties, changes in regional SL are larger than the total uncertainty by 2100, and pass the 90% significance level, for most ocean regions in both RCP4.5 and RCP8.5, whether trends are calculated for ocean-only processes that include global thermosteric SL change (Lyu et al., 2014; Richter and Marzeion, 2014; Carson et al., 2015; see **Figure 7B**), or for all forcing components of SL, including changes in land ice and water and global isostatic adjustment (Church et al., 2013; Lyu et al., 2014; see **Figure 7C**). Dynamic sea level changes alone emerge above the background variability only in high latitude regions, with few exceptions (**Figure 7A**), though there is substantial spread between models in the Southern Ocean (**Figure 7D**). The spread in the emergence time decreases everywhere when including changes in global thermosteric sea level (**Figure 7E**) and the other components of regional sea level change external to the climate models (**Figure 7F**). The coupled climate model changes in regional SL are larger than the noise (intermodel uncertainty, also called the ensemble spread, plus internal variability) in both the open ocean, and at the coast (Carson et al., under review). These model results are particularly due to the use of ensemble averaging to enhance the signal-to-noise ratio, though the uncertainty in dynamic SL between models is much larger than that due to internal model variability in 90–100-year trends (Little et al., 2015).

Improvements in climate model physics and parameterizations that could reduce intermodel spread (for an exploration of causes of intermodel spread, see, e.g., Gregory et al., 2016) and better account for potential systematic errors in projected SL should be a goal of the international modeling community. However, the way forward in model improvement is complex. Clearly, some improvement can be found by increasing resolution, both for the atmosphere (Spence et al., 2014) and the ocean (Sérazin et al., 2015), especially in the context of SL changes in the vicinity of the Antarctic Circumpolar Current (Saenko et al., 2015) and Antarctic continental shelf (Spence et al., 2017); but, for some regions, SL projections seem to lack a strong sensitivity to resolution (Suzuki et al., 2005; Penduff et al., 2011). Another idea is to include only models in multi-model ensembles that have been proven to locally reproduce the physics of heat uptake and circulation changes due to wind and buoyancy forcing found in ocean observations – what has been termed climate model tuning (Mauritsen et al., 2012). Regional SL projections can be sensitive to the ocean model parameterizations used, although Huber and Zanna (2017) estimated that air-sea flux uncertainties were larger than those due to model parameterizations.

Although at relatively coarse resolution, CMIP5 simulations can capture expected features of coastal SL variability. For example, Minobe et al. (2017) explain some of the western boundary coastal SL change evident in most CMIP5 model projections via a theory which describes a balance between mass input to the western boundary due to Rossby waves from the ocean interior and equatorward mass ejection due to coastal-trapped wave propagation. There is, however, evidence that coastal SL projections are improved in higher resolution models (e.g., Balmaseda et al., 2015). For this reason, dynamical downscaling with regional climate models has been used to study the effects of climate change scenarios at the coast (e.g., Meier, 2006; Liu et al., 2016; Zhang et al., 2016, 2017). Global climate models are, however, generally used for providing boundary conditions to the higher resolution regional climate models, and uncertainties in those conditions can still be a problem.

RECOMMENDATIONS FOR OBSERVING AND MODELING SYSTEMS

Observational Needs

In this section, we examine tide gauge and related GNSS networks. Space-based SL measurements and other ancillary observations are considered in the papers cited at the end

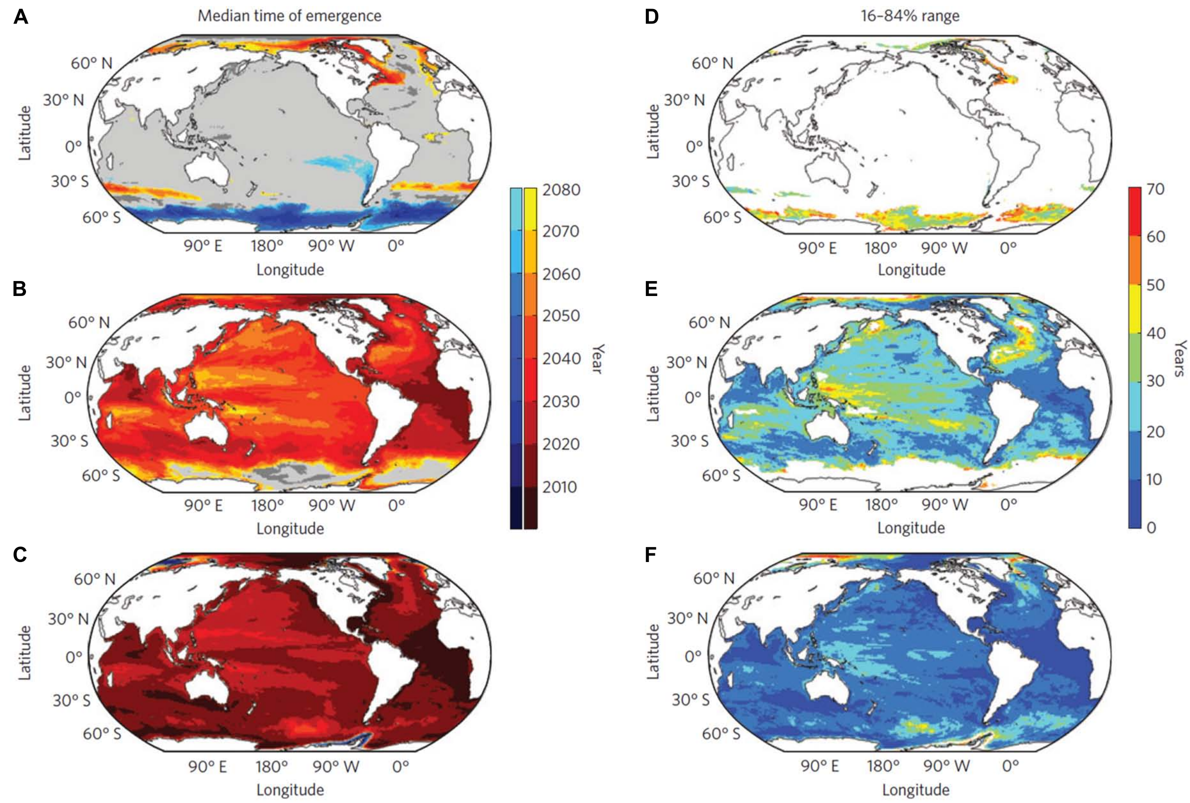

FIGURE 7 | Time after which changes in local sea level are always larger than modeled local sea level variability (ensemble median) under RCP8.5, by year, for: **(A)** dynamic sea level, **(B)** dynamic plus global thermosteric sea level, and **(C)** all contributing components to regional sea level. Gray color means that no signal has yet emerged by 2080 or no agreement between models. The 16–84% uncertainty ranges at regions where at least 84% of the models in the ensemble show signal emergence by 2080 are shown in the right panels **(D–F)** for the same sea level change projection estimates **(A–C)**. Adapted with permission from **Figure 2** of Lyu et al. (2014).

of section "Ancillary Observations." The tide gauge and GNSS observing systems are mature and have clear oversight and procedures for setting requirements. Here we focus on identifying weaknesses in the present systems as opposed to setting additional requirements. The idea is that the requirements are well-known, but the weaknesses that need attention in the implementation of the systems are not as well-described.

Tide Gauges

Presently national entities voluntarily contribute their tide gauge data to the centers associated with the global network (GLOSS), from which it follows inevitably that there are gaps where national monitoring is either limited, absent, or not provided to GLOSS for some reason. Many efforts have been made to complete the global tide gauge network and to densify it on a regional basis, but these attempts have often been short-lived, and even after gauges have been installed successfully the essential ongoing maintenance thereafter has been lacking. For example, great efforts were made several years ago to install new gauges in Africa (Woodworth et al., 2007) but many of these gauges are no longer operational for various reasons.

More recently, the requirements for regional networks for tsunami warning (especially in the Indian Ocean and the Caribbean) and in support of other ocean hazards (e.g., hurricane-induced storm surges in the Caribbean) have led to an effective regional densification of the tide gauge network, but the improvements are patchy and sometimes come with compromises in measuring techniques. For example, some gauges used for tsunami monitoring do not have the requirement for excellent datum control that is needed for SL and coastal studies.

The present geographical gaps in tide gauge recording can be seen, e.g., in **Figure 2**, but it is important to recognize that there are gaps that are more subtle than those shown simply as dots on maps. For example, some operators employ outdated technology instead of the modern types of tide gauge (acoustic, pressure and, increasingly, radar) and the associated new data loggers and data transmission systems, which can provide accurate data in real time (IOC, 2016). In addition, some operators lack the technical expertise or resources required to operate their existing stations to GLOSS standards, in spite of GLOSS having put major efforts into capacity building through the years. In some countries, the tide gauges and the essential leveling to land benchmarks for datum control are the responsibility of different agencies, which may restrict communication between the responsible people (Woodworth et al., 2017b). In others, there is a lack of sufficient experts, generally university researchers specializing in oceanography, geodesy or SL science, who can make cogent arguments for tide gauges to local funding agencies. Other examples of gaps include major ports whose owners are content to use tide tables based on short historical records, instead of operating their own gauges to modern standards, which would enable the data to also be used for research. In addition, some old tide gauge records still remain non-digitized, despite their value for climate studies (Bradshaw et al., 2015).

One overarching gap is a lack of funding on both national and international levels. At the international level, it is imperative that we have regional network managers (1) to keep a close watch for gauges that are experiencing data outages or other problems, (2) to help with the installation of new gauges, and (3) to undertake the necessary leveling and other tasks where those activities fall between agencies. This applies especially to regions such as Africa where there are few people playing such roles on a national basis. The only real solution to this problem is the provision of central funding to the implementing group, which is presently GLOSS. At the national level, recent GLOSS-related workshops have demonstrated the major differences between the considerable investment in new tide gauge infrastructure in some countries and the lack of it in others (IOC, 2018). In some cases, national networks are being privatized, which is related to national funding, and this raises potential concerns about data quality and data sharing in the future (Pérez Gómez et al., 2017).

The satellite altimeter community considers *in situ* measurements by tide gauges to be an important source of complementary SL information (Roemmich et al., 2017). Such missions, which cost tens of millions of dollars USD each, have been secured as part of international cooperation involving most space agencies. Unfortunately, this is currently not the case for the global tide gauge network that they rely on, despite the fact the needs of such network are only a few million dollars per year.

GNSS Stations

As discussed in section "Sea Level Observations," tide gauges are affected by VLM due to movements of the Earth's crust where the gauges are attached. For many key SL applications (e.g., long-term climate studies or satellite altimetry drift estimation) the climatic and VLM contributions to the SL observations need to be separated, meaning that it is crucial to precisely and independently correct the VLM at the tide gauge locations. Since the early 1990s, GPS has been the only constellation suitable for precise VLM corrections (Carter, 1994; Foster, 2015), but nowadays other satellite positioning constellations such as GLONASS, Galileo, and BeiDou are also being considered.

Although associating a GNSS permanent station to a tide gauge has been required for the GLOSS network stations for some time (IOC, 2012), there is still work to do in terms of GNSS-tide gauge co-locations (King, 2014). Also, we should remember that the original idea behind the GLOSS initiative to use GNSS was to provide vertical positions and rates for the tide gauge benchmarks that are used to vertically reference the tide gauges (Carter, 1994). As the system evolved, however, the GNSS stations and the resulting VLM estimates were not always tied to the benchmarks and are therefore not directly related to the motion of the tide gauge zero point (Woodworth et al., 2017b). This prevents the absolute positioning of the tide gauges, and leaves questions as to the relevance of the GNSS VLM rates to the tide gauge zero point rates.

To be more specific, GNSS/tide gauge co-location data are provided in the SONEL databank (see text footnote 6), which is recognized as the GLOSS data center for GNSS. About 80% of the GLOSS tide gauges have a permanent GNSS station closer than 15 km (**Figure 8**), but many of these stations were not installed specifically for the monitoring of the tide gauge zero point, which explains why only 28% are closer than 500 m. This also explains the lack of direct ties to the tide gauge benchmarks mentioned above. This raises two issues. First, one cannot make a reliable geodetic link by conventional methods between the GNSS and tide gauge instruments when they are more than 1 km apart, which partly explains why only 29% of the GLOSS GNSS-co-located tide gauges have a geodetic tie available at SONEL. Second, if the GNSS and tide gauge zero point are not directly tied, then one must assume that the GNSS is measuring the same land movement that occurs at the tide gauge. Unless regular leveling campaigns are done between both instruments, this assumption is tenuous. Thus, we highly recommend that GNSS stations be installed as near as possible to the tide gauge site, and to carry out regular leveling campaigns when it is not.

Finally, there is also an issue in terms of the VLM velocities that are available at present. There is currently one published GNSS solution dedicated to tide gauges, which was developed at the University of La Rochelle (Santamaría-Gómez et al., 2017), but other global velocity fields are available (Altamimi et al., 2016; Blewitt et al., 2016)[13]. For users, questions arises as to which solution to use, as these have substantial differences despite using essentially the same data. The GNSS VLM rates gain in accuracy when the data are processed by the largest number of analysis centers using different software and strategies, which is why it is crucial to make GNSS data freely available to the community. The International Association of Geodesy, through the Joint Working Group 3.2, currently focuses on constraining VLM at tide gauges by combining all the available global GPS VLM fields consistently into a single solution available to the sea-level community. This combined solution also allows examining the level of coherence between the different VLM estimates and their reproducibility by the different analysis centers.

Modeling Needs

Typical CMIP SL projections are a hybrid product, in the sense that some components (e.g., thermosteric changes) are an intrinsic part of CMIP simulations and others (e.g., SL changes related to land ice melt) are calculated off-line using CMIP output. The off-line calculations do not account for possible feedbacks in the climate system. In addition, for coastal projections, CMIP simulations are generally used only as boundary conditions for coastal forecasting models (e.g., Kopp et al., 2014).

An important part of projected SL trends on a regional scale arises from the dynamical and thermal and haline adjustment of

[13] See also https://sideshow.jpl.nasa.gov/post/series.html

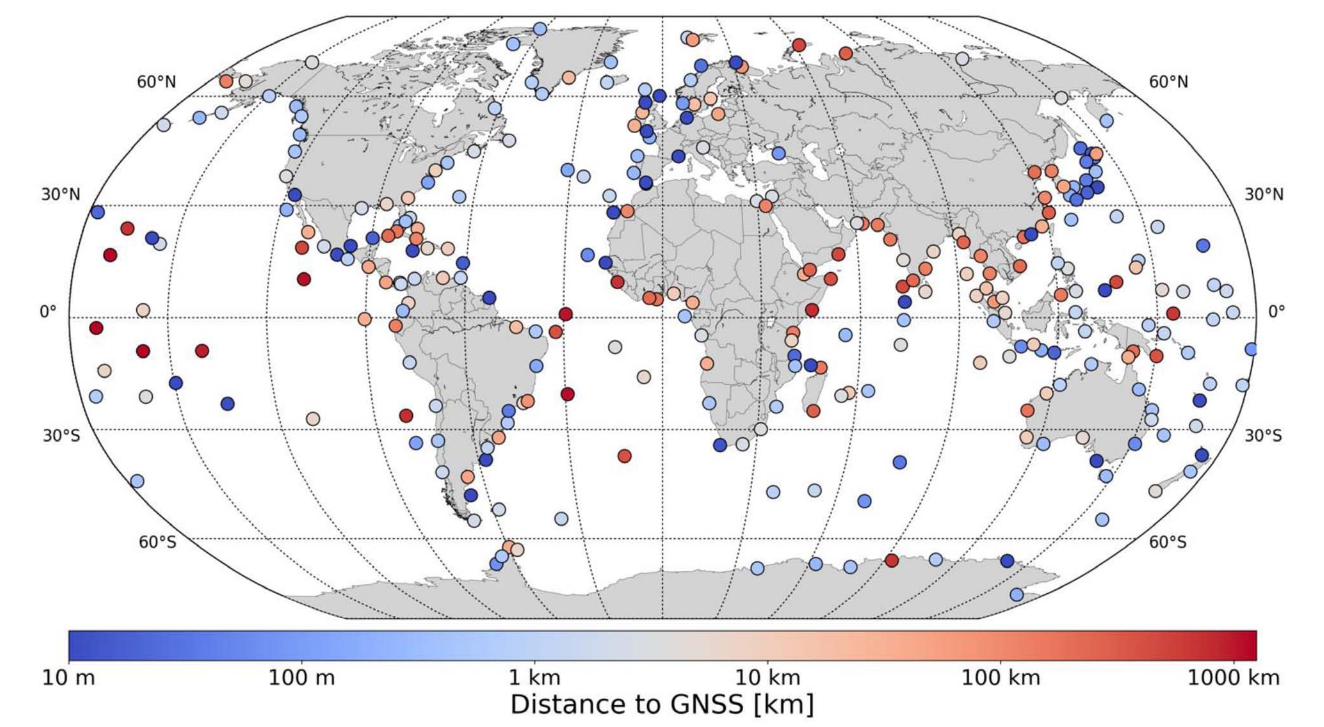

FIGURE 8 | Distance between tide gauge and GNSS stations.

the ocean related to changes in the circulation. On timescales up to decades, model improvements are needed to better capture the interannual variability of SL associated with climate modes discussed in section "Causes of Coastal Sea Level Variability" (e.g., Frankcombe et al., 2013; Carson et al., 2017). Simulations of such variability by climate models require further validation with emerging longer data sets of SL, mass or density changes.

At the same time, climate change also affects the cryosphere and terrestrial water storage, causing global mass changes in the ocean resulting in regional patterns (fingerprints) controlled by gravitational and rotational physics, as well as vertical motions of the sea floor (Slangen et al., 2014; Carson et al., 2016). For CMIP5 and before, these cryospheric/hydrologic changes were calculated off-line based on temperature and precipitation fields available from those coupled climate models (Church et al., 2013). The reasons to do so are manifold, as explained below.

If we consider the contribution from glaciers around the world, a key issue is that the spatial resolution that is required for glacier modeling is much finer than the spatial resolution of climate models. This mismatch is not easy to overcome and is therefore usually circumvented with off-line downscaling techniques, using as basic input the spatial and temporal variability from the climate models.

For the contribution of ice sheets, the required fine spatial scales remain an issue. The required scales for driving ice sheets are of the order 10 km and still smaller than what climate models typically resolve, though within reach of regional climate models. Some model experiments (Vizcaíno et al., 2013) show for instance that the surface mass balance of Greenland is reasonably well reproduced. Unfortunately, producing a reliable surface mass balance is only part of the problem, as forcing of the ice sheets is not only driven by the atmosphere but also by the ocean, particularly in Antarctica (Jenkins, 1991; Rignot et al., 2013; Lazeroms et al., 2018).

Changes in water mass characteristics on the continental shelves around Antarctica are generally believed to be the driving force behind the observed ice mass loss in West Antarctica (Joughin et al., 2014; Rignot et al., 2014). Warmer circumpolar water has likely led to increased basal melt rates forming the primary driver for changes in the area. Improved modeling of the basal melt rates in the cavities below the ice shelves requires first of all improved insight in the geometry of those cavities, and secondly very fine resolution ocean models to resolve the small-scale patterns controlling the water flow on the continental shelves. Nested ocean models may be a way forward as a complement to insights revealed from specialized fine resolution global models (e.g., Goddard et al., 2017; Spence et al., 2017).

Beside issues arising from the limited spatial resolutions of climate models, a second type of problem arises from the fact that the response timescales of ice sheets is far longer than for atmospheric processes and even significantly longer than for ocean processes. Hence initialization is a serious problem (Nowicki et al., 2016). This is specifically addressed by Goelzer et al. (2018) showing the wide variation in modeling results for the Greenland ice sheet depending on the initial shape and height of the present-day ice sheet. A way forward is to used remote sensing data that provides strong constraints on the mass loss over recent decades (Cazenave et al., 2018; Shepherd et al., 2018), which could constrain the dynamical imbalance of ice sheet models. Similarly, the dynamic state in terms of ice velocity as derived from InSAR observations can be used as a constraint to invert the spatially variable basal traction parameter (Morlighem et al., 2010). Several studies using data assimilation techniques (e.g., Seroussi et al., 2011) indicate that further improvements on the dynamical state are possible.

Finally, ice sheet models, which are generally believed to be the largest source of uncertainty on centennial timescales, are not yet integrated in climate models in part because our physical understanding remains limited. The grounding line physics controlling the boundary between the floating ice shelves and the grounded ice are now understood reasonably well (Pattyn et al., 2012). At the same time, it has become apparent that the stability of the ice sheet is not only dependent on the retrograde slope condition, underlying the classical marine ice sheet instability mechanism, but that the combination of hydrofracturing (Rott et al., 1996) and marine ice cliff instability (Bassis and Walker, 2012) may lead to a rapid disintegration of the ice sheet, as hypothesized by DeConto and Pollard (2016).

As a result of all the physically coupled, but currently poorly constrained processes associated with coupling of the ice sheets to climate models, fresh water fluxes produced by melting ice are not captured in the climate models (Bronselaer et al., 2018). This limitation might affect the circulation and sea ice formation in the Southern Ocean (e.g., Bintanja et al., 2013), which may feedback on the basal melt rates and accumulation on the ice sheet. Hosing experiments have been carried out in the past (Stouffer et al., 2006), but more refined fully coupled experiments are still needed.

Independent of improvements of coupling ice sheet and climate models, we have to consider improvements in the modeling skills of subsidence. This requires careful calibration of climate models, before they can be used as input for hydro-(geo)logical models, and additional assumptions on the socio-economic pathways not captured by the traditional climate model output. Full coupling seems out of the question due to spatial scale discrepancy between climate model and subsidence, but a more comprehensive aggregation seems feasible.

Beside improvements on regional SL projections as described above, there is a need to improve our projection skills with respect to near coastal conditions. Near the coast, SL projections are much more complicated because many small-scale dynamical processes (e.g., storm surges, tides, wind-waves, river runoff) and bathymetric features play a dominant role in determining extreme SL events and also affect longer period variability (see section "Causes of Coastal Sea Level Variability"). For this purpose, COFS (section "Coastal Models and Sea Level Forecasts") need to be considered.

A main requirement for improving COFS for coastal SL is efficient downscaling techniques or nesting strategies. For example, Ranasinghe (2016) proposed a modeling framework for a local scale climate change impact quantification study on sandy coasts, starting from a global climate model ensemble, downscaled to regional climate model ensemble, which are then bias corrected and used to force regional scale coastal forcing models (waves, ocean dynamics, riverflows), which finally force local scale coastal impact models (such as Delft3D). Procedures include not only the assessment of the boundary conditions, but also the refinement of model set-ups, involving the grid, the topographic details and the various associated forcing, thereby addressing land-sea, air-sea, and coastal-offshore interactions (Kourafalou et al., 2015a,b). A realistic and detailed bathymetry is critical for COFS, since global models do not provide adequate coverage of shallow coastal areas and estuaries. As beaches are dynamic, changes in bathymetry should be explicitly modeled and include wetting and drying schemes (e.g., Warner et al., 2013). At the land-ocean interface, a particular challenge for forecasts of coastal SL changes and related circulation is the determination of realistic river inflows, since these values either come from river gauges, or from climatology or hydrological models. In addition to that, the correct representation of the river plume dynamics in COFS can also be challenging (e.g., Schiller and Kourafalou, 2010; Schiller et al., 2011). Further use of coupled modeling approaches is also important. For example, predicted surges can be significantly enhanced during extreme storm events when considering wave-current interactions (Staneva et al., 2016a, 2017).

Another promising avenue for improving the ability to project changes in extreme SL in coastal regions is the use of global, unstructured grid hydrodynamical models that can simulate extreme surge events (Muis et al., 2016), in combination with information on large-scale SL and atmospheric forcing available from CMIP-type calculations. This approach allows one to project changes in risk over time resulting from changes in both mean SL and extremes. In addition, improvements in projections of wave climate (Hemer et al., 2012; Morim et al., 2018) offer a possibility to better resolve changes in extremes caused by waves (Arns et al., 2017).

In the future, COFS can benefit substantially from improved data collection and availability, along with better characterization of measurement errors. For example, technological innovations such as Ka-band and SAR altimetry, as used in missions such as AltiKa and CryoSat-2, have contributed to the improvement of coastal altimetry techniques (Benveniste et al., 2019). Wide-swath altimetry promises further improvements (Morrow et al., 2019). Developments in many other data types (hydrography, bathymetry, coastal radar, coastal runoff, surface meteorology), discussed in other OceanObs'19 contributions, will all have an impact on the ability to forecast coastal SL. For any data type, it is important that the statistics of measurement errors (variances and covariances, dependences in space and time) be specified as best as possible, to be able to optimally inform the data assimilation systems.

DEVELOPING FUTURE SEA LEVEL SERVICES

With more than 600 million people living in low elevation coastal areas less than 10 m above mean SL (McGranahan et al., 2007), and around 150 million people living within 1 m of the high tide level (Lichter et al., 2011), future SL rise is one of the most damaging aspects of a warming climate (Intergovernmental

Panel on Climate Change [IPCC], 2013). Considering the 0.9 m global mean SL rise under RCP8.5 scenario, global annual flood costs without additional adaptation are projected to be US$ 14.3 trillion per year (2.5% of global GDP), and up to 10% of GDP for some countries (Jevrejeva et al., 2018). Adaptation could potentially reduce SL induced flood costs by a factor of 10 (Hinkel et al., 2014; Jevrejeva et al., 2018; Vousdoukas et al., 2018).

Global Sea Level is one of seven key indicators defined by the World Meteorological Organisation within the Global Climate Observing System Program to describe the changing climate. The importance of, as a minimum, maintaining existing SL observing systems cannot be overstated. More generally, the availability of coastal observations, scientific analysis and interpretation of such measurements, and future projections of SL rise in a warming climate are crucial for impact assessment, risk management, adaptation strategy and long-term decision making in coastal areas.

For risk assessment, decisions about adaptation to local SL rise, and resilience to coastal flooding, erosion and other changes in coastal areas, there is a need for SL services to support and empower stakeholders (e.g., governments, local authorities, coastal engineers, planners, socio-economists and coastal communities). In addition to existing climate services (e.g., those laid out in the report "A European research and innovation roadmap for climate services," such as the Copernicus Climate Change Service)[14], which ensure that climate research provides benefits and solutions to the challenges facing our society, there is an urgent necessity for specific equivalent expertise in coastal SL changes. An equivalent set of SL services could cover the transformation of data, together with other relevant information, into customized products such as projections, forecasts, information, trends, economic analysis, assessments (including technology assessment), counseling on best practices, development and evaluation of solutions and any other SL-related service that may be of use for the society at large.

To frame present status and future development of SL services that can address the challenges facing coastal communities, it is useful to consider the example of PSMSL (introduced in section "Existing Observing Systems"). Established in 1933, PSMSL is the global data bank for long term SL change information from tide gauges (**Figure 2**, section "Sea Level Observations"). Over the past few decades PSMSL has been providing the SL community with additional services relating to the acquisition, analysis, interpretation of SL data and a wide range of advice to tide gauge operators and data analysts.

With new challenges due to climate change and SL rise there is an urgent need worldwide to support decisions on managing exposure to climate variability and change. The PSMSL will address these needs by offering a range of services including expert advice, bespoke climate information, value added services and solutions to help build capacity in developing countries.

Using the expanding knowledge of climate and SL science, expertise in past and future SL changes, and a growing understanding of how climate hazards impact society and the environment, PSMSL is currently developing a new framework (including a set of products) that will be vital for empowering decision-makers in coastal cities, small island states and local communities to respond to the risks and opportunities of climate variability and change. With the main focus on developing countries, new PSMSL products (e.g., **Figure 9**) will support climate-smart decisions to make coastal societies more resilient to SL rise and climate change, and meet international capacity development objectives, ensuring that public investment in climate science can be used to maximum effect.

The PSMSL has experience working with more than 200 data authorities and close co-operation with GLOSS/Intergovernmental Oceanographic Commission/European Global Ocean Observing System, and therefore has the opportunity to take a world-leading role to develop and deliver a suite of SL services. For example, PSMSL already provides products[15] globally, regionally and nationally and will develop these further, particularly drawing on its expertise to support decision-makers.

In addition to PSMSL, a variety of agencies and research groups have demonstrated leadership in this arena. In the United States, multiple frameworks have been developed to combine information about future SL rise with land-use, economic, and demographic data to inform decision makers and map regions of enhanced risk (e.g., NOAA's Sea Level Rise Viewer[16]; Climate Central's Risk Zone Map[17]). These frameworks can serve as examples on which to build services for other regions. As SL continues to rise and flooding events become more common, it will become increasingly important to develop tools that provide short-term forecasts of problematic coastal conditions. For example, UHSLC provides seasonal SL

[14]https://climate.copernicus.eu/

[15]https://www.psmsl.org/products/

[16]https://coast.noaa.gov/slr/

[17]https://ss2.climatecentral.org/#12/

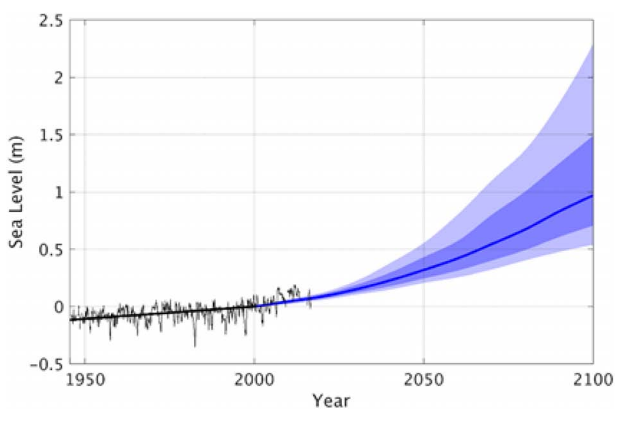

FIGURE 9 | Tide gauge observations (black lines) combined with sea level projections (blue) with RCP 8.5 scenarios at Kwajalein, Marshall Islands (Jackson and Jevrejeva, 2016). The thin black line is monthly tide gauge record, the thick black line is long-term linear trend; the thick blue line is sea level projection at 50% probability, and the dark and light blue shading areas represent 17–83 and 5–95% probabilities, respectively.

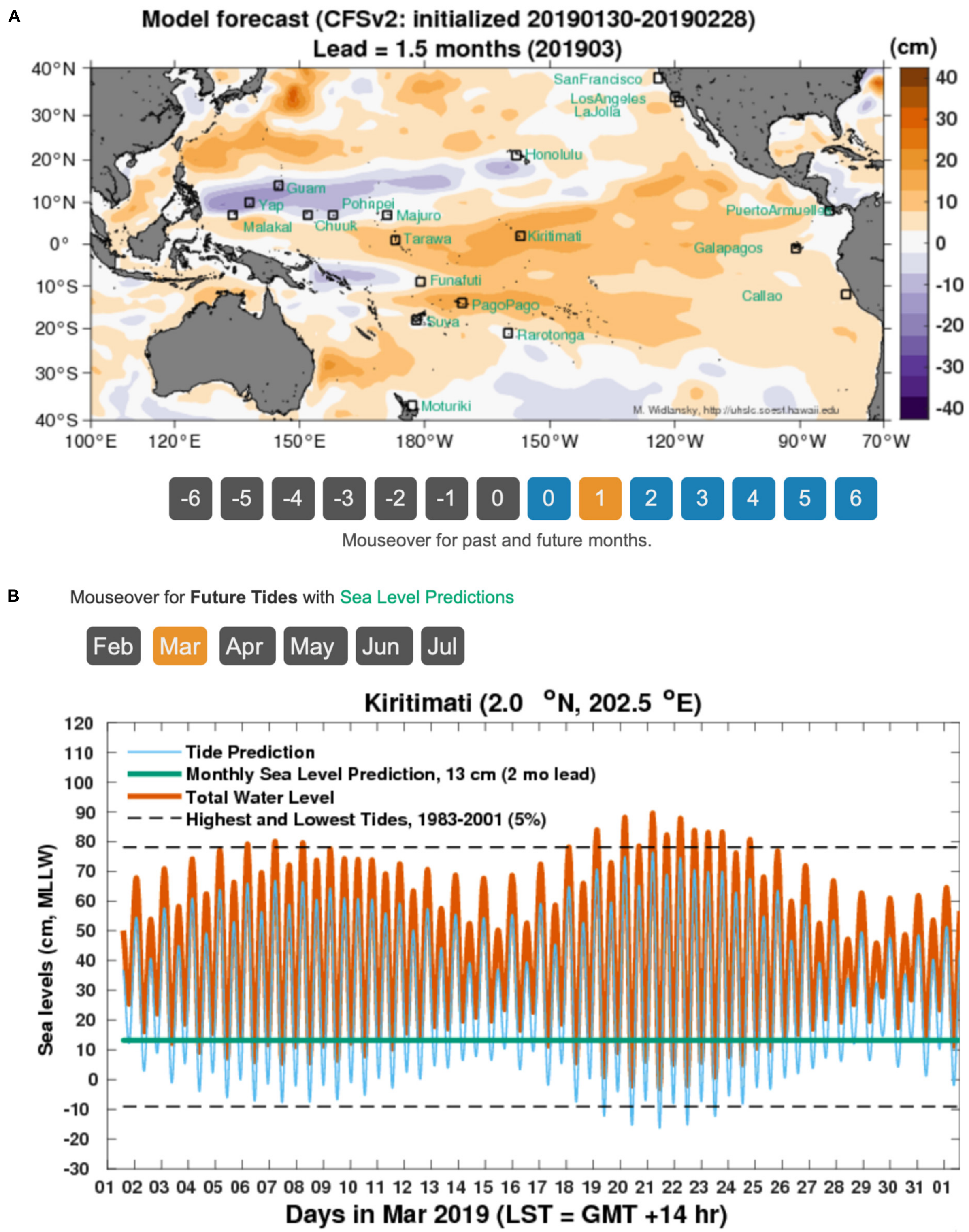

FIGURE 10 | University of Hawai'i Sea Level Center's seasonal forecast product of monthly mean sea level (Widlansky et al., 2017). **(A)** Sea level forecast for the tropical Pacific with 1 month lead from an operational forecast model. **(B)** Astronomical tide predictions plus forecasted mean sea level with 1 month lead for the island of Kiritimati. The combination of tides plus mean sea level provides a more accurate forecast of high tide and potential impacts compared to astronomical predictions alone.

forecasts to Pacific Island communities (**Figure 10**)[18], which combine output from state-of-the-art operational models with local tide predictions to give local stakeholders advanced notice of likely tidal flooding conditions. The web-based product is supplemented by an active email forecast discussion group with local weather services, and work is currently underway to expand to United States continental coastlines. At even shorter timescales of days to weeks, it is possible to forecast the gravity wave field of the ocean and, by extension, the impact of these waves on total water level at the coastline. The USGS Total Water Level and Coastal Change Forecast Viewer[19] provides one example of how short-term forecasts of SL, tide, and waves can be combined to provide decision makers with comprehensive view of imminent conditions to drive science-supported action. These examples provide a basis for further development, but are by no means comprehensive. Providing necessary sea level services for all regions of need will require international collaboration and cooperation between research centers, national agencies, and local authorities.

Examples of continued and future developments include:

- Localized SL projections to inform local development and mitigation plans;
- Development of software capable of performing automatic quality control of tide gauge data;
- Low cost temporary tide gauges for surveys in remote areas;
- Identification of locally relevant flooding thresholds that identify specific elements of at-risk infrastructure;
- Regional storm surge and inundation forecasting.

The Sea Level Futures Conference (Liverpool, United Kingdom, July 2–4, 2018), celebrating the 85th anniversary of PSMSL, reviewed the present status of SL science knowledge, covering key aspects of SL change. Special emphasis was given to existing SL observations, synthesis of available data and discussion of future novel observational techniques in coastal areas. The science provides clear evidence that SL is rising and this is already impacting vulnerable coastal areas, especially those with rapidly growing urban populations and associated infrastructure. Addressing these challenges in a warming climate requires integrated sustainable and continued observations, data products and advanced modeling capability. Thus, as recognized by conference participants, there is a requirement for close collaboration between scientists from different disciplines and the broad stakeholder community to develop plans for responding to SL change, storm surges and flood risk affecting the coastal zone. Key actions necessary to enable the development of SL services that can effectively support adaptation and mitigation measures and empower decision-makers in coastal communities should include:

- Commitment to sustained, systematic and complementary global and coastal measurements of SL and its components to understand observed variability and change, to constrain longer term projections and to improve skill of forecasting and early warning systems. This commitment must be in line with efforts under the Global Ocean Observing System, Global Geodetic Observing System, GLOSS and other programs.
- Commitment to extend the historical SL record through data rescue, digitization and the accurate detailed integration of historic tide gauge data into international repositories to reduce spatial and temporal gaps and to validate process-understanding as well as process-based climate models, and to detect and attribute the influence of natural (intrinsic and externally forced) and human-induced drivers.
- Broad-scale assessment of uplift/subsidence, especially human-induced subsidence, to guide analysis of local SL change. The international community should take steps to provide all available information (e.g., from GNSS or InSAR) about uplift/subsidence in coastal areas. This work should involve the use of GNSS at all tide gauge stations (as per GLOSS standards) and the maintenance of an accurate International Terrestrial Reference Frame.
- Implementation of a multi-purpose approach to tide gauge networks, focusing on the requirements of all users (e.g., scientists, port authorities, coastal engineers and hazard forecasters), to ensure the sustainability of such networks. This is particularly important when establishing stations in developing economies (e.g., most of Africa), where existing networks tend to be deficient. Tide gauge measurements, including past records, are essential for improving our knowledge of coastal SL variability, which is one of the main gaps in SL science.
- Implementation of comprehensive observations in coastal areas, including expansion of *in situ* and satellite SL measurements, VLM, waves, sediment transport and relevant ancillary observations (e.g., bathymetry, river runoff), with special emphasis on monitoring changes in vulnerable coastal zones where a variety of climate and non-climate related processes interact (e.g., deltas, cities, small island states).
- Development of new technologies for SL observations on both coastal and global scales, e.g., low cost tide gauges and low cost GNSS units fitted to buoys/floating platforms, GNSS-reflectometry, coastal altimetry and wide-swath altimetry.
- Development of improved coastal SL projections and forecasts, involving dedicated data efforts for model advancement, exploration of new assimilation schemes and downscaling techniques, and accounting for the additional key processes at work in the coastal zone (e.g., tides, wave run-up, storm surges, river discharge).
- Quantitative assessment of uncertainties in all data streams, to improve monitoring activities and advance modeling and assimilation systems, and all SL projection and forecast products, along with clear understanding of different contributors to observed coastal SL variability and change (e.g., climate modes, intrinsic ocean fluctuations, anthropogenic forcing, VLM).

[18]https://uhslc.soest.hawaii.edu/sea-level-forecasts/

[19]https://coastal.er.usgs.gov/hurricanes/research/twlviewer/

- Closer and wider cooperation between the scientific community, stakeholders, policy- and decision-makers to ensure that SL products are accessible and are used correctly and appropriately to facilitate adaptation and mitigation measures for vulnerable coastal areas (e.g., cities, deltas, small islands).

AUTHOR CONTRIBUTIONS

This paper resulted from the merger, suggested by OceanObs'19 organizers, of three different abstracts led by RP, SJ, and GM. RP provided the original outline, coordinated the writing, and assembled the final paper. PW, MM, MCi, MCa, GM, RvdW, SJ, and CD led the writing of different sections, with input from CH, WH, AM, CP, TP, AS-G, DS, GW and others. All authors participated in the group discussions that led to the final contents of the manuscript.

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REFERENCES

Altamimi, Z., Rebischung, P., Métivier, L., and Xavier, C. (2016). ITRF2014: a new release of the International Terrestrial Reference Frame modeling nonlinear station motions. *J. Geophys. Res. Solid Earth* 121, 6109–6131. doi: 10.1002/2016JB013098

Ampou, E. E., Johan, O., Menkes, C. E., Niño, F., Birol, F., Ouillon, S., et al. (2017). Coral mortality induced by the 2015-2016 El-Niño event in Indonesia: the effect of rapid sea level fall. *Biogeoscience* 14, 817–826. doi: 10.5194/bg-14-817-2017

Andres, M., Gawarkiewicz, G. G., and Toole, J. M. (2013). Interannual sea level variability in the western North Atlantic: regional forcing and remote response. *Geophys. Res. Lett.* 40, 5915–5919. doi: 10.1002/2013GL058013

Ardhuin, F., Stopa, J. E., Chapron, B., Collard, F., Husson, R., Jensen, R. E., et al. (2019). Observing sea states. *Front. Mar. Sci.* 6:124. doi: 10.3389/fmars.2019.00124

Arns, A., Dangendorf, S., Jensen, J., Talke, S., Bender, J., and Pattiaratchi, C. (2017). Sea level rise induced amplification of coastal protection design heights. *Sci. Rep.* 7:40171. doi: 10.1038/srep40171

Bajo, M., and Umgiesser, G. (2010). Storm surge forecast through a combination of dynamic and neural network models. *Ocean Model.* 33, 1–9. doi: 10.1016/j.ocemod.2009.12.007

Balmaseda, M. A., Hernandez, F., Storto, A., Palmer, M. D., Alves, O., Shi, L., et al. (2015). The ocean reanalyses intercomparison project (ORA-IP). *J. Oper. Oceanogr.* 8, s80–s97. doi: 10.1080/1755876X.2015.1022329

Barnard, P. L., Short, A. D., Harley, M. D., Splinter, K. D., Vitousek, S., Turner, I. L., et al. (2015). Coastal vulnerability across the Pacific dominated by El Niño/Southern Oscillation. *Nat. Geosci.* 8, 801–807. doi: 10.1038/NGEO2539

Barth, A., Alvera-Azcárate, A., Beckers, J.-M., Rixen, M., and Vandenbulcke, L. (2007). Multigrid state vector for data assimilation in a two-way nested model of the Ligurian Sea. *J. Mar. Syst.* 65, 41–59. doi: 10.1016/j.jmarsys.2005.07.006

Bassis, J., and Walker, C. (2012). Upper and lower limits on the stability of calving glaciers from the yield strength envelope of ice. *Proc. R. Soc. A.* 468, 913–931. doi: 10.1098/rspa.2011.0422

Becker, M., Karpytchev, M., Marcos, M., Jevrejeva, S., and Lennartz-Sassink, S. (2016). Do climate models reproduce the complexity of observed sea level changes? *Geophys. Res. Lett.* 43, 5176–5184. doi: 10.1002/2016GL068971

Benveniste, J., Cazenave, A., Vignudelli, S., Fenoglio-Marc, L., Shah, R., Almar, R., et al. (2019). Requirements for a coastal zone observing system. *Front. Mar. Sci.* 6:348. doi: 10.3389/fmars.2019.00348

Bingham, R. J., and Hughes, C. W. (2012). Local diagnostics to estimate density-induced sea level variations over topography and along coastlines. *J. Geophys. Res.* 117:C01013. doi: 10.1029/2011JC007276

Bintanja, R., van Oldenborgh, G. J., Drijfhout, S. S., Wouters, B., and Katsman, C. A. (2013). Important role for ocean warming and increased ice-shelf melt in Antarctic sea-ice expansion. *Nat. Geosci.* 6, 376–379. doi: 10.1038/ngeo1767

Blewitt, G., Kreemer, C., Hammond, W. C., and Gazeaux, J. (2016). MIDAS robust trend estimator for accurate GPS station velocities without step detection. *J. Geophys. Res.* 121, 2054–2068. doi: 10.1002/2015JB012552

Bradshaw, E., Rickards, L., and Aarup, T. (2015). Sea level data archaeology and the Global Sea Level Observing System(GLOSS). *Geophys. Res. J.* 6, 9–16. doi: 10.1016/j.grj.2015.02.005

Brink, K. H. (1998). "Deep-sea forcing and exchange processes," in *The Sea, The Global Coastal Ocean: Processes and Methods*, Vol. 10, eds K. H. Brink and A. R. Robinson (New York,NY: Wiley).

Bronselaer, B., Winton, M., Griffies, S. M., Hurlin, W. J., Rodgers, K. B., Sergienko, O. V., et al. (2018). Change in future climate due to Antarctic melting. *Nature* 564, 53–58. doi: 10.1038/s41586-018-0712-z

Calafat, F. M., Chambers, D. P., and Tsimplis, M. N. (2012). Mechanisms of decadal sea level variability in the eastern North Atlantic and the Mediterranean sea. *J. Geophys. Res.* 117:C09022. doi: 10.1029/2012JC008285

Calafat, F. M., Chambers, D. P., and Tsimplis, M. N. (2013). Inter-annual to decadal sea-level variability in the coastal zones of the Norwegian and Siberian seas: the role of atmospheric forcing. *J. Geophys. Res. Oceans* 118, 1287–1301. doi: 10.1002/jgrc.20106

Calafat, F. M., Chambers, D. P., and Tsimplis, M. N. (2014). On the ability of global sea level reconstructions to determine trends and variability. *J. Geophys. Res. Oceans* 119, 1572–1592. doi: 10.1002/2013JC009298

Calafat, F. M., Wahl, T., Lindsten, F., Williams, J., and Frajka-Williams, E. (2018). Coherent modulation of the sea-level annual cycle in the United States by Atlantic Rossby waves. *Nat. Commun.* 9:2571. doi: 10.1038/s41467-018-04898-y

Carson, M., Köhl, A., and Stammer, D. (2015). The impact of regional multidecadal and century-scale internal climate variability on sea level trends in CMIP5 models. *J. Clim.* 28, 853–861. doi: 10.1175/JCLI-D-14-00359.1

Carson, M., Köhl, A., Stammer, D., Meyssignac, B., Church, J., Schröter, J., et al. (2017). Regional sea level variability and trends, 1960–2007: a comparison of sea level reconstructions and Ocean syntheses. *J. Geophys. Res. Oceans* 122, 9068–9091. doi: 10.1002/2017JC012992

Carson, M., Köhl, A., Stammer, D., Slangen, A. B. A., Katsman, C., van de Wal, A. R. S. W., et al. (2016). Coastal sea level changes, observed, and projected during the 20th and 21st century. *Clim. Change* 134, 269–281. doi: 10.1007/s10584-015-1520-1

Carter, W. E. (ed.) (1994). *Report of the Surrey Workshop of the IAPSO Tide Gauge Bench Mark Fixing Committee. Report of a meeting held 13-15 December 1993 at the Institute of Oceanographic Sciences Deacon Laboratory*. NOAA Technical Report NOSOES0006. Silver Spring, MD: NOAA, 81.

Cazenave, A., Ablain, M., Bamber, J., Barletta, V., Beckley, B., and Benveniste, J. (2018). Global Sea Level Budget 1993-present. *Earth Syst. Sci. Data* 10, 1551–1590. doi: 10.5194/essd-10-1551-2018

Cazenave, A., Le Cozannet, G., Benveniste, J., and Woodworth, P. (2017). *Monitoring the Change of Coastal Zones from Space*. Available at: https://eos.org/opinions/monitoring-coastal-zone-changes-from-space (accessed November 02, 2017).

Chambers, D. P., Wahr, J., and Nerem, R. S. (2004). Preliminary observations of global ocean mass variations with GRACE. *Geophys. Res. Lett.* 31:L13310. doi: 10.1029/2004GL020461

Chassignet, E. P., Hurlburt, H. E., Smedstad, O. M., Halliwell, G. R., Hogan, P. J., Wallcraft, A. J., et al. (2007). The HYCOM (Hybrid Coordinate Ocean Model) data assimilative system. *J. Mar. Syst.* 65, 60–83. doi: 10.1016/j.jmarsys.2005.09.016

Chassignet, E. P., Smith, L. T., and Halliwell, G. R. (2003). North Atlantic simulations with the hybrid coordinate ocean model (HYCOM): impact of the vertical coordinate choice, reference pressure and thermobaricity. *J. Phys. Oceanogr.* 33, 2504–2526.

Chelton, D. B., and Enfield, D. B. (1986). Ocean signals in tide gauge records. *J. Geophys. Res.* 91, 9081–9098. doi: 10.1029/JB091iB09p09081

Chepurin, G. A., Carton, J. A., and Leuliette, E. (2014). Sea level in ocean reanalyses and tide gauges. *J. Geophys. Res. Oceans* 119, 147–155. doi: 10.1002/2013JC009365

Chini, N., Stansby, P., Leake, J., Wolf, J., and Roberts-Jones, J. (2010). The impact of sea level rise and climate change on inshore wave climate: a case study for East Anglia (UK). *Coast. Eng.* 57, 973–984. doi: 10.1016/j.coastaleng.2010.05.009

Church, J. A., Clark, P. U., Cazenave, A., Gregory, J. M., Jevrejeva, S., Levermann, A., et al. (2013). "Sea Level Change," in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, et al. (Cambridge: Cambridge University Press).

Cipollini, P., Benveniste, J., Birol, F., Fernandes, M. J., Obligis, E., Passaro, M., et al. (2017a). "Satellite Altimetry in coastal regions," in *Satellite Altimetry Over Oceans and Land Surfaces: Earth Observation of Global Changes Book Series*, eds D. Stammer and A. Cazenave (London: CRC Press), 644.

Cipollini, P., Calafat, F. M., Jevrejeva, S., Melet, A., and Prandi, P. (2017b). Monitoring sea level in the coastal zone with satellite altimetry and tide gauges. *Surv. Geophys.* 38, 33–57. doi: 10.1007/s10712-016-9392-0

Cronin, M. F., Gentemann, C. L., Edson, J., Ueki, I., Bourassa, M., Brown, S., et al. (2019). Air-sea fluxes with a focus on heat and momentum. *Front. Mar. Sci.* 6:430. doi: 10.3389/fmars.2019.00430

Dangendorf, S., Marcos, M., Woppelmann, G., Conrad, C. P., Frederikse, T., and Riva, R. (2017). Reassessment of 20th century global mean sea level rise. *Proc. Natl. Acad. Sci. U.S.A.* 114, 5946–5951. doi: 10.1073/pnas.1616007114

Davis, J. L., and Vinogradova, N. T. (2017). Causes of accelerating sea level on the East Coast of North America. *Geophys. Res. Lett.* 44, 5133–5141. doi: 10.1002/2017GL072845

De Mey-Frémaux, P., Ayoub, N., Barth, A., Brewin, B., Charria, G., Campuzano, F., et al. (2019). Model-observations synergy in the coastal ocean. *Front. Mar. Sci.* 6:436. doi: 10.3389/fmars.2019.00436

DeConto, R. M., and Pollard, D. (2016). Contribution of Antarctica to past and future sea level rise. *Nature* 531, 591–597. doi: 10.1038/nature17145

Douglas, B. C. (1991). Global sea level rise. *J. Geophys. Res.* 96, 6981–6992. doi: 10.1029/91JC00064

Dunne, R. P., Barbosa, S. M., and Woodworth, P. L. (2012). Contemporary sea level in the Chagos Archipelago, central Indian Ocean. *Glob. Planet. Change* 8, 25–37. doi: 10.1016/j.gloplacha.2011.11.009

Emery, K. O., and Aubrey, D. G. (1991). *Sea Levels, Land Levels, and Tide Gauges*. New York, NY: Springer-Verlag, 237.

Enfield, D. B., and Allen, J. S. (1980). On the structure and dynamics of monthly mean sea level anomalies along the Pacific coast of North and South America. *J. Phys. Oceanogr.* 10, 557–578. doi: 10.1175/1520-0485(1980)010<0557:otsado>2.0.co;2

Engelhart, S. E., and Horton, B. P. (2012). Holocene sea level database for the Atlantic coast of the United States. *Quat. Sci. Rev.* 54, 12–25. doi: 10.1016/j.quascirev.2011.09.013

Ezer, T., and Atkinson, L. P. (2014). Accelerated flooding along the U.S. East Coast: on the impact of sea-level rise, tides, storms, the Gulf Stream, and the North Atlantic Oscillations. *Earths Future* 2, 362–382. doi: 10.1002/2014EF000252

Ezer, T., Atkinson, L. P., Corlett, W. B., and Blanco, J. L. (2013). Gulf Stream's induced sea level rise and variability along the U.S. mid-Atlantic coast. *J. Geophys. Res.* 118, 685–697. doi: 10.1002/jgrc.20091

Fenoglio-Marc, L., Dinardo, S., Scharroo, R., Roland, A., Dutour, M., Lucas, B., et al. (2015). The German Bight: a validation of CryoSat-2 altimeter data in SAR mode. *Adv. Space Res.* 55, 2641–2656. doi: 10.1016/j.asr.2015.02.014

Feyen, J. C., Funakoshi, Y., van der Westhuysen, A. J., Earle, S., Caruso Magee, C., Tolman, H. L., et al. (2013). "Establishing a Community-Based Extratropical Storm Surge and Tide Model for NOAA's Operational Forecasts for the Atlantic and Gulf Coasts," in *Proceedings of the 93rd AMS Annual Meeting*, Austin, TX.

Firing, Y. L., and Merrifield, M. A. (2004). Extreme sea level events at Hawaii: influence of mesoscale eddies. *Geophys. Res. Lett.* 31:L24306. doi: 10.1029/2004GL021539

Foster, J. (2015). "GPS and surveying," in *Handbook of Sea-Level Research*, eds I. Shennan, A. J. Long, and B. P. Horton (Hoboken, NJ: John Wiley & Sons), doi: 10.1002/9781118452547.ch10

Fox-Kemper, B., Adcroft, A. J., Boning, C. W., Chassignet, E. P., Curchitser, E., and Danabasoglu, G. (2019). Challenges and prospects in ocean circulation models. *Front. Mar. Sci.* 6:65. doi: 10.3389/fmars.2019.00065

Frankcombe, L. M., Spence, P., Hogg, A. M. C., England, M. H., and Griffies, S. M. (2013).). Sea level changes forced by Southern Ocean winds. *Geophys. Res. Lett.* 457, 5710–5715. doi: 10.1002/2013GL058104

Frederikse, T., Simon, K., Katsman, C. A., and Riva, R. (2017). The sea-level budget along the Northwest Atlantic coast: GIA, mass changes, and large-scale ocean dynamics. *J. Geophys. Res. Oceans* 122, 5486–5501. doi: 10.1002/2017JC012699

French, J., Mawdsley, E., Fujiyama, T., and Achuthan, K. (2017). Combining machine learning with computational hydrodynamics for prediction of tidal surge inundation at estuarine ports. *Procedia IUTAM* 25, 28–35. doi: 10.1016/j.piutam.2017.09.005

Goddard, P., Dufour, C. O., Yin, J., Griffies, S. M., and Winton, M. (2017). CO2-induced ocean warming around the Antarctic ice sheet in an eddying global climate model. *J. Geophys. Res.*. 122, 8079–8101. doi: 10.1002/2017JC012849

Goelzer, H., Nowicki, S., Edwards, T., Beckley, M., Abe-Ouchi, A., and Aschwanden, A. (2018). Design and results of the ice sheet model initialization experiments initMIP-Greenland: an ISMIP6 intercomparison. *Cryosphere* 12, 1433–1460. doi: 10.5194/tc-12-1433-2018

Gregory, J. M., Bouttes, N., Griffies, S. M., Haak, H., Hurlin, W., Jungclaus, J., et al. (2016). The Flux-Anomaly-Forced Model Intercomparison Project (FAFMIP) contribution to CMIP6: investigation of sea-level and ocean climate change in response to CO2 forcing. *Geosci. Model Dev.* 9, 3993–4017. doi: 10.5194/gmd-9-3993-2016

Gregory, J. M., Griffies, S. M., Hughes, C. W., Lowe, J. A., Church, J. A., Fukumori, I., et al. (2019). Concepts and terminology for sea level–mean, variability and change, both local and global. *Surv. Geophys.* doi: 10.1007/s10712-019-09525-z

Gulev, S. K., Grigorieva, V., Sterl, A., and Woolf, D. (2003). Assessment of the reliability of wave observations from voluntary observing ships: insights from the validation of a global wind wave climatology based on voluntary observing ship data. *J. Geophys. Res.* 108:3236. doi: 10.1029/2002JC001437

Han, W., Meehl, G. A., Hu, A., Zheng, J., Kenigson, J., and Vialard, J. (2017). Decadal variability of indian and pacific walker cells: do they co-vary on decadal timescales? *J. Clim.* 30, 8447–8468. doi: 10.1175/JCLI-D-16-0783.1

Han, W., Stammer, D., Meehl, G. A., Hu, A., Sienz, F., and Zhang, L. (2018). Multi-decadal trend and decadal variability of the regional sea level over the indian ocean since the 1960s: roles of climate modes and external forcing. *Climate* 6:51. doi: 10.3390/cli6020051

Hemer, M. A., Wang, X. L., Weisse, R., and Swail, V. R. (2012). Advancing wind-waves climate science: the COWCLIP project. *Bull. Am. Meteorol. Soc.* 93, 791–796. doi: 10.1175/BAMS-D-11-00184.1

Heslop, E. E., Ruiz, S., Allen, J., López-Jurado, J. L., Renault, L., and Tintoré, J. (2012). Autonomous underwater gliders monitoring variability at "choke points" in our ocean system: a case study in the Western Mediterranean Sea. *Geophys. Res. Lett.* 39:L20604. doi: 10.1029/2012GL053717

Higginson, S., Thompson, K. R., Woodworth, P. L., and Hughes, C. W. (2015). The tilt of mean sea level along the east coast of North America. *Geophys. Res. Lett.* 42, 1471–1479. doi: 10.1002/2015GL063186

Hinkel, J., Lincke, D., Vafeidis, A. T., Perrette, M., Nicholls, R. J., Tol, R. S. J., et al. (2014). Future coastal flood damage and adaptation costs. *Proc. Natl. Acad. Sci. U.S.A.* 111, 3292–3297. doi: 10.1073/pnas.1222469111

Hogarth, P. (2014). Preliminary analysis of acceleration of sea level rise through the twentieth century using extended tide gauge data sets (August 2014). *J. Geophys. Res. Oceans* 119, 7645–7659. doi: 10.1002/2014JC009976

Holgate, S. J., Matthews, A., Woodworth, P. L., Rickards, L. J., Tamisiea, M. E., Bradshaw, E., et al. (2013). New data systems and products at the Permanent Service for Mean Sea Level. *J. Coast. Res.* 29, 493–504. doi: 10.2112/JCOASTRES-D-12-00175.1

Holgate, S. J., and Woodworth, P. L. (2004). Evidence for enhanced coastal sea level rise during the 1990s. *Geophys. Res. Lett.* 31:L07305. doi: 10.1029/2004GL019626

Holman, R. A., and Stanley, J. (2007). The history and technical capabilities of Argus. *Coast. Eng.* 54, 477–491. doi: 10.1016/j.coastaleng.2007.01.003

Hu, A., and Bates, S. C. (2018). Internal climate variability and projected future regional steric and dynamic sea level rise. *Nat. Comm.* 9:1068. doi: 10.1038/s41467-018-03474-8

Hu, A., Meehl, G. A., Stammer, D., Han, W., and Strand, W. G. (2017). Role of perturbing ocean initial condition in simulated regional sea level change. *Water* 9:402. doi: 10.3390/w9060401

Huber, M. B., and Zanna, L. (2017). Drivers of uncertainty in simulated ocean circulation and heat uptake. *Geophys. Res. Lett.* 44, 1402–1413. doi: 10.1002/2016GL071587

Hughes, C. W., Fukumori, I., Griffies, S. M., Huthnance, J. M., Minobe, S., Spence, J. P., et al. (2019). Sea level and the role of coastal trapped waves in mediating the interaction between the coast and open ocean. *Surv. Geophys.* doi: 10.1007/s10712-019-09535-x

Hughes, C. W., and Meredith, M. P. (2006). Coherent sea-level fluctuations along the global continental slope. *Philos. Trans. R. Soc. A* 364, 885–901. doi: 10.1098/rsta.2006.1744

Hughes, C. W., Tamisiea, M. E., Bingham, R. J., and Williams, J. (2012). Weighing the ocean: using a single mooring to measure changes in the mass of the ocean. *Geophys. Res. Lett.* 39:L17602. doi: 10.1029/2012GL052935

Hughes, C. W., Williams, J., Blaker, A., Coward, A., and Stepanov, V. (2018). A window on the deep ocean: the special value of ocean bottom pressure for monitoring the large-scale, deep-ocean circulation. *Progr. Oceanogr.* 161, 19–46. doi: 10.1016/j.pocean.2018.01.011

Hughes, C. W., Williams, J., Hibbert, A., Boening, C., and Oram, J. (2016). A Rossby whistle: a resonant basin mode observed in the Caribbean Sea. *Geophys. Res. Lett.* 43, 7036–7043. doi: 10.1002/2016GL069573

Hughes, C. W., and Williams, S. D. P. (2010). The color of sea level: importance of spatial variations in spectral shape for assessing the significance of trends. *J. Geophys. Res.* 115:C10048. doi: 10.1029/2010JC006102

Idier, D., Bertin, X., Thompson, P., and Pickering, M. D. (2019). Interactions between mean sea level, tide, surge, waves and flooding: mechanisms and contributions to sea level variations at the coast. *Surv. Geophys.* doi: 10.1007/s10712-019-09549-5

Idier, D., Paris, F., Le Cozannet, G., Boulahya, F., and Dumas, F. (2017). Sea-level rise impacts on the tides of the European Shelf. *Cont. Shelf Res.* 137, 56–71. doi: 10.1016/j.csr.2017.01.007

IOC (2012). *The Global Sea Level Observing System (GLOSS) Implementation Plan - 2012. UNESCO/Intergovernmental Oceanographic Commission*. IOC Technical Series No. 100. Paris: IOC, 37.

IOC (2016). *Manual on Sea-level Measurements and Interpretation, Volume V: Radar Gauges. Paris, Intergovernmental Oceanographic Commission of UNESCO*. IOC Manuals and Guides No.14, vol. V; JCOMM Technical Report No. 89. Paris: IOC, 104.

IOC (2018). *Workshop on Sea-Level Measurements in Hostile Conditions, Moscow, Russian Federation, 13-15 March 2018. Intergovernmental Oceanographic Commission of UNESCO*. IOC Workshop Reports, 281. Paris: UNESCO, 28.

Intergovernmental Panel on Climate Change [IPCC] (2013). "Intergovernmental Panel on Climate Change (IPCC) Summary for policymakers," in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, et al. (Cambridge: Cambridge University Press).

Intergovernmental Panel on Climate Change [IPCC] (2014). *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Summaries, Frequently Asked Questions, and Cross-Chapter Boxes. A Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, et al. (Geneva: World Meteorological Organization), 190.

Jackson, L. P., and Jevrejeva, S. (2016). A probabilistic approach to 21st century regional sea-level projections using RCP and High-end scenarios. *Glob. Planet. Change* 146, 179–189. doi: 10.1016/j.gloplacha.2016.10.006

Jenkins, A. (1991). A one-dimensional model of ice shelf-ocean interaction. *J. Geophys. Res.-Oceans* 96, 20671–20677. doi: 10.1029/91JC01842

Jevrejeva, S., Jackson, L. P., Grinsted, A., Lincke, D., and Marzeion, B. (2018). Flood damage costs under the sea level rise with warming of 1.5 °*C and* 2 °C. *Environ. Res. Lett.* 13:074014. doi: 10.1088/1748-9326/aacc76

Jevrejeva, S., Moore, J. C., Grinsted, A., Matthews, A. P., and Spada, G. (2014). Trends and acceleration in global and regional sea levels since 1807. *Glob. Planet. Change* 113, 11–22. doi: 10.1016/j.gloplacha.2013.12.004

Johnson, C. S., Miller, K. G., Browning, J. V., Kopp, R. E., Kahn, N. E., Fan, Y., et al. (2018). The role of sediment compaction and groundwater withdrawal in local sea-level rise, Sandy Hook, New Jersey, USA. *Quat. Sci. Rev.* 181, 30–42. doi: 10.1016/j.quascirev.2017.11.031

Joughin, I., Smith, B. E., and Medley, B. (2014). Marine ice sheet collapse potentially under way for the thwaites glacier basin, West Antarctica. *Science* 344, 735–738. doi: 10.1126/science.1249055

Karegar, M. A., Dixon, T. H., and Engelhart, S. E. (2016). Subsidence along the Atlantic Coast of North America: insights from GPS and late Holocene relative sea level data. *Geophys. Res. Lett.* 43, 3126–3133. doi: 10.1002/2016GL068015

Kemp, A. C., Bernhardt, C. E., Horton, B. P., Kopp, R. E., Vane, C. H., and Peltier, W. R. (2014). Late Holocene sea- and land-level change on the U.S. southeastern Atlantic coast. *Mar. Geol.* 357, 90–100. doi: 10.1016/j.margeo.2014.07.010

Kenigson, J. S., Han, W., Rajagopalan, B., Yanto, and Jasinksi, M. (2018). Decadal shift of NAO-linked interannual sea level variability along the U.S. Northeast Coast. *J. Clim.* 31, 4981–4989. doi: 10.1175/JCLI-D-17-0403.1

Kerr, P. C., Martyr, R. C., Donahue, A. S., Hope, M. E., Westerink, J. J., Luettich, R. A. Jr., et al. (2013). U.S. IOOS coastal and ocean modeling testbed: evaluation of tide, wave, and hurricane surge response sensitivities to mesh resolution and friction in the Gulf of Mexico. *J. Geophys. Res. Oceans* 118, 4633–4661. doi: 10.1002/jgrc.20305

King, M. A. (2014). *Priorities for Installation of Continuous Global Navigation Satellite System (GNSS) near to Tide Gauges, Technical Report to GLOSS*. Tasmania, VIC: University of Tasmania.

Kopp, R. E., Horton, R. M., Little, C. M., Mitrovica, J. X., Oppenheimer, M., Rasmussen, D. J., et al. (2014). Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earths Future* 2, 383–406. doi: 10.1002/2014EF000239

Kourafalou, V. H., De Mey, P., Le Henaff, M., Charria, G., Edwards, C. A., He, R., et al. (2015a). Coastal ocean forecasting: system integration and evaluation. *J. Operat. Oceanogr.* 8, S127–S146. doi: 10.1080/1755876X.2015.1022336

Kourafalou, V. H., De Mey, P., Staneva, J., Ayoub, N., Barth, A., Chao, Y., et al. (2015b). Coastal ocean forecasting: science foundation and user benefits. *J. Operat. Oceanogr.* 8, S147–S167. doi: 10.1080/1755876X.2015.1022348

Landerer, F. W., and Volkov, D. L. (2013). The anatomy of recent large sea level fluctuations in the Mediterranean Sea. *Geophys. Res. Lett.* 40, 1–5. doi: 10.1002/grl.50140

Larson, K. M., Ray, R. D., and Williams, S. D. P. (2017). A 10-year comparison of water levels measured with a geodetic GPS receiver versus a conventional tide gauge. *J. Atmos. Oceanic Tech.* 34, 295–307. doi: 10.1175/JTECH-D-16-0101.1

Lazeroms, W. M. J., Jenkins, A., Gudmundsson, G. H., and van de Wal, R. S. W. (2018). Modelling present-day basal melt rates for Antarctic ice shelves using a parameterization of buoyant meltwater plume. *Cryosphere* 12, 49–70. doi: 10.5194/tc-12-49-2018

Le Traon, P. Y., Antoine, D., Bentamy, A., Bonekamp, H., Breivik, L. A., Chapron, B., et al. (2015). Use of satellite observations for operational oceanography: recent achievements and future prospects. *J. Oper. Oceanogr.* 8(Suppl.1), s12–s27. doi: 10.1080/1755876X.2015.1022050

Li, Z., Chao, Y., McWilliams, J. C., and Ide, K. (2008). A three-dimensional variational data assimilation scheme for the regional ocean modelling system. *J. Atmos. Ocean Technol.* 25, 2074–2090. doi: 10.1175/2008JTECHO594.1

Lichter, M., Vafeidis, A. T., Nicholls, R. J., and Kaiser, G. (2011). Exploring data-related uncertainties in analyses of land area and population in the 'low-elevation coastal zone' (LECZ). *J. Coast. Res.* 27, 757–768. doi: 10.2112/JCOASTRES-D-10-00072.1

Little, C. M., Horton, R. M., Kopp, R. R., Oppenheimer, M., and Yip, S. (2015). Uncertainty in twenty-first-century CMIP5 sea level projections. *J. Clim.* 28, 838–852. doi: 10.1175/JCLI-D-14-00453.1

Liu, Z.-J., Minobe, S., Sasaki, Y. N., and Terada, M. (2016). Dynamical downscaling of future sea-level change in the western North Pacific using ROMS. *J. Oceanogr.* 72, 905–922. doi: 10.1007/s10872-016-0390-0

Llovel, W., Penduff, T., Meyssignac, B., Molines, J.-M., Terray, L., BessieÌres, L., et al. (2018). Contributions of atmospheric forcing and chaotic ocean variability to regional sea level trends over 1993–2015. *Geophys. Res. Lett.* 45, 13405–13413. doi: 10.1029/2018GL080838

Lyu, K., Zhang, X., Church, J. A., Slangen, A. B. A., and Hu, J. (2014). Time of emergence for regional sea-level change. *Nat. Clim. Change* 4, 1006–1010. doi: 10.1038/nclimate2397

Marcos, M., Puyol, B., Wöppelmann, G., Herrero, C., and García-Fernández, M. J. (2011). The long sea level record at Cadiz (southern Spain) from 1880 to 2009. *J. Geophys. Res.* 116:C12003. doi: 10.1029/2011JC007558

Marcos, M., and Tsimplis, M. N. (2007). Variations of the seasonal sea level cycle in southern Europe. *J. Geophys. Res.* 112:C12011. doi: 10.1029/2006JC004049

Marcos, M., and Woodworth, P. L. (2017). Spatio-temporal changes in extreme sea levels along the coasts of the North Atlantic and the Gulf of Mexico. *J. Geophys. Res. Oceans* 122, 7031–7048. doi: 10.1002/2017JC013065

Marcos, M., Wöppelmann, G., Matthews, A., Ponte, R. M., Birol, F., Ardhuin, F., et al. (2019). Coastal sea level and related fields from existing observing systems. *Surv. Geohys.* doi: 10.1007/s10712-019-09513-3

Martin, M. J., Balmaseda, M., Bertino, L., Brasseur, P., Brassington, G., Cummings, J., et al. (2015). Status and future of data assimilation in operational oceanography. *J. Operat. Oceanogr.* 8, s28–s48. doi: 10.1080/1755876X.2015.1022055

Mauritsen, T., Stevens, B., Roeckner, E., Crueger, T., Esch, M., Giorgetta, M., et al. (2012). Tuning the climate of a global model. *J. Adv. Model. Earth Sys.* 4:M00A01. doi: 10.1029/2012MS000154

McCarthy, G. D., Haigh, I. D., Hirschi, J. J.-M., Grist, J. P., and Smeed, D. A. (2015). Ocean impact on decadal Atlantic climate variability revealed by sea-level observations. *Nature* 521, 508–510. doi: 10.1038/nature14491

McGranahan, G., Balk, D., and Anderson, B. (2007). The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. *Environ. Urban* 19, 17–37. doi: 10.1177/0956247807076960

Meier, H. E. M. (2006). Baltic Sea climate in the late twenty-first century:a dynamical downscaling approach using two global models and two emission scenarios. *Clim. Dyn.* 27, 39–68. doi: 10.1007/s00382-006-0124-x

Melet, A., and Meyssignac, B. (2015). Explaining the spread in global mean Thermosteric sea level rise in CMIP5 climate models. *J. Clim.* 28, 9918–9940. doi: 10.1175/JCLI-D-15-0200.1

Melet, A., Meyssignac, B., Almar, R., and Le Cozannet, G. (2018). Under-estimated wave contribution to coastal sea-level rise. *Nat. Clim. Change* 234, 234–239. doi: 10.1038/s41558-018-0088-y

Menéndez, M., and Woodworth, P. L. (2010). Changes in extreme high water levels based on a quasi-global tide-gauge dataset. *J. Geophys. Res.* 115:C10011. doi: 10.1029/2009JC005997

Merrifield, M. A., Genz, A. S., Kontoes, C. P., and Marra, J. J. (2013). Annual maximum water levels from tide gauges: contributing factors and geographic patterns. *J. Geophys. Res.* 118, 2535–2546.

Meyssignac, B., Piecuch, C. G., Merchant, C. J., Racault, M.-F., Palanisamy, H., MacIntosh, C., et al. (2017a). Causes of the regional variability in observed sea level, sea surface temperature and ocean colour over the period 1993–2011. *Surv. Geophys.* 38, 187–215. doi: 10.1007/s10712-016-9383-1

Meyssignac, B., Slangen, A. B. A., Melet, A., Church, J., Fettweis, X., and Marzeion, B. (2017b). Evaluating model simulations of twentieth-century sea-level rise. Part II: regional sea-level change. *J. Clim.* 30, 8565–8593. doi: 10.1175/JCLI-D-17-0112.1

Minobe, S., Terada, M., Qiu, B., and Schneider, N. (2017). Western boundary sea level: a theory, rule of thumb, and application to climate models. *J. Phys. Oceanogr.* 47, 957–977. doi: 10.1175/JPO-D-16-0144.1

Mitchum, G. T. (1995). The source of 90-day oscillations at Wake Island. *J. Geophys. Res.* 100, 2459–2475. doi: 10.1029/94JC02923

Morim, J., Hemer, M. A., Cartwright, N., Strauss, D., and Andutta, F. (2018). On the concordance of 21st century wind-wave climate projections. *Glob. Planet. Change* 167, 160–171. doi: 10.1016/j.gloplacha.2018.05.005

Morlighem, M., Rignot, E., Seroussi, H., Larour, E., Ben Dhia, H., and Aubry, D. (2010). Spatial patterns of basal drag inferred using control methods from a full-Stokes and simpler models for Pine Island Glacier, West Antarctica. *Geophys. Res. Lett.* 37:L14502. doi: 10.1029/2010GL043853

Morrow, R., Fu, L.-L., Ardhuin, F., Benkiran, M., Chapron, B., Cosme, E., et al. (2019). Global observations of fine-scale ocean surface topography with the surface water and ocean topography (SWOT) mission. *Front. Mar. Sci.* 6:232. doi: 10.3389/fmars.2019.00232

Muis, S., Verlaan, M., Winsemius, H. C., Aerts, J. C. J. H., and Ward, P. J. (2016). A global reanalysis of storm surges and extreme sea levels. *Nat. Commun.* 7:37. doi: 10.1038/ncomms11969

Nowicki, S. M. J., Payne, A., Larour, E., Seroussi, H., Goelzer, H., Lipscomb, W., et al. (2016). Ice sheet model intercomparison project (ISMIP6) contribution to CMIP6. *Geosci. Model Dev.* 9, 4521–4545. doi: 10.5194/gmd-9-4521-4201

Pattyn, F., Shoof, C., Perichon, L., Hindmarsh, R. C. A., Bueler, E., de Fleurian, B., et al. (2012). Results of the marine ice sheet model intercomparison project, MISMIP. *Cryosphere* 6, 573–588. doi: 10.5194/tc-6-573-2012

Penduff, T., Juza, M., Barnier, B., Zika, J., Dewar, W. K., Treguier, A.-M., et al. (2011). Sea level expression of intrinsic and forced ocean variabilities at interannual time scales. *J. Clim.* 24, 5652–5670. doi: 10.1175/JCLI-D-11-00077.1

Penduff, T., Sérazin, G., Leroux, S., Close, S., Molines, J.-M., Barnier, B., et al. (2018). Chaotic variability of ocean heat content: climate-relevant features and observational implications. *Oceanography* 31, 63–71. doi: 10.5670/oceanog.2018.210

Pérez Gómez, B., Donato, V., Hibbert, A., Marcos, M., Raicich, F., and Hammarklint, T. (2017). "Recent Efforts for an Increased Coordination of Sea Level Monitoring in Europe: EuroGOOS Tide Gauge Task Team," in *Proceedings of the International WCRP/IOC Conference 2017: Regional Sea Level Changes and Costal Impacts*, New York, NY.

Piecuch, C. G., Bittermann, K., Kemp, A. C., Ponte, R. M., Little, C. M., Engelhart, S. E., et al. (2018a). River-discharge effects on United States Atlantic and Gulf coast sea-level changes. *Proc. Natl. Acad. Sci.U.S.A.* 115, 7729–7734. doi: 10.1073/pnas.1805428115

Piecuch, C. G., Landerer, F. W., and Ponte, R. M. (2018b). Tide gauge records reveal improved processing of gravity recovery and climate experiment time-variable mass solutions over the coastal ocean. *Geophys. J. Int.* 214, 1401–1412. doi: 10.1093/gji/ggy207

Piecuch, C. G., and Ponte, R. M. (2015). Inverted barometer contributions to recent sea level changes along the northeast coast of North America. *Geophys. Res. Lett.* 42, 5918–5925. doi: 10.1002/2015GL064580

Piecuch, C. G., Thompson, P. R., and Donohue, K. A. (2016). Air pressure effects on sea level changes during the twentieth century. *J. Geophys. Res. Oceans* 121, 7917–7930. doi: 10.1002/2016JC012131

Polster, A., Fabian, M., and Villinger, H. (2009). Efective resolution and drift of Paroscientifc pressure sensors derived from long-term seafoor measurements. *Geochem. Geophys. Geosyst.* 10:Q08008. doi: 10.1029/2009GC002532

Prandi, P., Cazenave, A., and Becker, M. (2009). Is coastal mean sea level rising faster than the global mean? A comparison between tide gauges and satellite altimetry over 1993-2007. *Geophys. Res. Lett.* 36:L05602. doi: 10.1029/2008GL036564

Pugh, D. T., and Woodworth, P. L. (2014). *Sea-Level Science: Understanding Tides, Surges, Tsunamis and Mean Sea-Level Changes*. Cambridge: Cambridge University Press, 408.

Queffeulou, P. (2013). "Merged altimeter wave height data. An update," in *Proceedings of the 'ESA Living Planet Symposium 2013'*, Edinburgh, 9–13.

Ranasinghe, R. (2016). Assessing climate change impacts on open sandy coasts: a review. *Earth Sci. Rev.* 160, 320–332. doi: 10.1016/j.earscirev.2016.07.011

Richter, K., and Marzeion, B. (2014). Earliest local emergence of forced dynamic and steric sea-level trends in climate models. *Environ. Res. Lett.* 9:114009. doi: 10.1088/1748-9326/9/11/114009

Rignot, E., Jacobs, S., Mouginot, J., and Scheuchl, B. (2013). Ice-shelf melting around Antarctica. *Science* 341, 266–270. doi: 10.1126/science.1235798

Rignot, E., Mouginot, J., Morlighem, M., Seroussi, H., and Scheuchl, B. (2014). Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011. *Geophys. Res. Lett.* 41, 3502–3509. doi: 10.1002/2014GL060140

Roemmich, D., Woodworth, P., Jevrejeva, J., Purkey, S., Lankhorst, M., Send, U., et al. (2017). "In situ observations needed to complement, validate, and interpret satellite altimetry," in *Satellite Altimetry Over Oceans and Land Surfaces*, eds D. Stammer and A. Cazenave (Boca Raton, FL: CRC Press), 113–147.

Rott, H., Skvarca, P., and Nagler, T. (1996). Rapid collapse of northern Larsen Ice Shelf. *Antarct. Sci.* 271, 788–792. doi: 10.1126/science.271.5250.788

Rudnick, D. L., Zaba, K. D., Todd, R. E., and Davis, R. E. (2017). A climatology of the California current system from a network of underwater gliders. *Progr. Oceanogr.* 154, 64–106. doi: 10.1016/j.pocean.2017.03.002

Saenko, O. A., Yang, D., Gregory, J. M., Spence, P., and Myers, P. G. (2015). Separating the influence of projected changes in air temperature and wind on patterns of sea level change and ocean heat content. *J. Geophys. Res. Oceans* 120, 5749–5765. doi: 10.1002/2015JC010928

Santamaría-Gómez, A., Gravelle, M., Dangendorf, S., Marcos, M., Spada, G., and Wöppelmann, G. (2017). Uncertainty of the 20th century sea-level rise due to vertical land motion errors. *Earth Planet. Sci. Lett.* 473, 24–32. doi: 10.1016/j.epsl.2017.05.038

Santamaría-Gómez, A., and Watson, C. (2017). Remote leveling of tide gauges using GNSS reflectometry: case study at Spring Bay. *Aust. GPS Solut.* 21, 451–459. doi: 10.1007/s10291-016-0537-x

Sasaki, Y. N., Minobe, S., and Miura, Y. (2014). Decadal sea-level variability along the coast of Japan in response to ocean circulation changes. *J. Geophys. Res. Oceans* 119, 266–275. doi: 10.1002/2013JC009327

Schiller, R. V., and Kourafalou, V. H. (2010). Modelling river plume dynamics with the hybrid coordinate ocean model. *Ocean Model.* 33, 101–117. doi: 10.1016/j.ocemod.2009.12.005

Schiller, R. V., Kourafalou, V. H., Hogan, P., and Walker, N. D. (2011). The dynamics of the Mississippi river plume: impact of topography, wind and offshore forcing on the fate of plume waters. *J. Geophys. Res.* 116, 1978–2012. doi: 10.1029/2010JC006883

Schramek, T. A., Colin, P. L., Merrifield, M. A., and Terrill, E. J. (2018). Depth-dependent thermal stress around corals in the tropical Pacific Ocean, Travis et al. *Geophys. Res. Lett.* 45, 9739–9747. doi: 10.1029/2018GL078782

Seneviratne, S. I., Nicholls, N., Easterling, D., Goodess, C. M., Kanae, S., Kossin, J., et al. (2012). "Changes in climate extremes and their impacts on the natural physical environment," in *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC)*, eds C. B. Field, V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, et al. (Cambridge: Cambridge University Press), 109–230.

Sérazin, G., Meyssignac, B., Penduff, T., Terray, L., Barnier, B., and Molines, J.-M. (2016). Quantifying uncertainties on regional sea-level rise induced by multi-decadal oceanic intrinsic variability. *Geophys. Res. Lett.* 43, 8151–8159. doi: 10.1002/2016GL069273

Sérazin, G., Penduff, T., Barnier, B., Molines, J., Arbic, B. K., Müller, M., et al. (2018). Inverse cascades of kinetic energy as a source of intrinsic variability: a global OGCM study. *J. Phys. Oceanogr.* 48, 1385–1408. doi: 10.1175/JPO-D-17-0136.1

Sérazin, G., Penduff, T., Grégorio, S., Barnier, B., Molines, J.-M., and Terray, L. (2015). Intrinsic variability of sea level from global ocean simulations: spatiotemporal scales. *J. Clim.* 28, 4279–4292. doi: 10.1175/JCLI-D-14-00554.1

Seroussi, H., Morlighem, M., Rignot, E., Larour, E., Aubry, D., Ben Dhia, H., et al. (2011). Ice flux divergence anomalies on 79north Glacier. *Greenland. Geophys Res Lett.* 38:L09501. doi: 10.1029/2011GL047338

Shchepetkin, A. F., and McWilliams, J. C. (2005). The regional oceanic modeling system (ROMS): a split-explicit, free-surface, topography-following-coordinate oceanic model. *Ocean Model.* 9, 347–404. doi: 10.1016/j.ocemod.2004.08.002

Shepherd, A., Ivins, E., Rignot, E., Smith, B., van den Broeke, M., Velicogna, I., et al. (2018). Mass balance of the Antarctic Ice Sheet from 1992 to 2017. *Nature* 558, 219–222. doi: 10.1038/s41586-018-0179-y

Simpson, J. H., and Sharples, J. (2012). *Introduction to the Physical and Biological of the Shelf Seas*. Cambridge: Cambridge University Press, 424. doi: 10.1017/CBO9781139034098

Slangen, A. B. A., Carson, M., Katsman, C., van de Wal, R., Koehl, A., Vermeersen, L., et al. (2014). Projecting twenty-first century regional sea-level changes. *Clim. Change* 124, 317–332. doi: 10.1007/s10584-014-1080-1089

Spence, P., Griffies, S. M., England, M. H., Mc, C., Hogg, A., Saenko, O. A., et al. (2014). Rapid subsurface warming and circulation changes of Antarctic coastal waters by poleward shifting winds. *Geophys. Res. Lett.* 41, 4601–4610. doi: 10.1002/2014GL060613

Spence, P., Holmes, R. M., McC Hogg, A., Griffies, S. M., Stewart, K. D., and England, M. H. (2017). Localized rapid warming of West Antarctic Peninsula subsurface waters by remote winds. *Nat. Clim. Change* 7, 595–603. doi: 10.1038/NCLIMATE3335

Stammer, D., Agarwal, N., Herrmann, P., Köhl, A., and Mechoso, R. (2011). Sea level response to Greenland ice melting in a coupled climate model. *Surv. Geophys.* 32, 621–642. doi: 10.1007/s10712-011-9142-2

Stanev, E. V., Schulz-Stellenfleth, J., Staneva, J., Grayek, S., Grashorn, S., Behrens, A., et al. (2016). Ocean forecasting for the German bight: from regional to coastal scales. *Ocean Sci.* 12, 1105–1136. doi: 10.5194/os-12-1105-2016

Staneva, J., Alari, V., Breivik, O., Bidlot, J.-R., and Mogensen, K. (2017). Effects of wave-induced forcing on a circulation model of the North Sea. *Ocean Dyn.* 67:81. doi: 10.1007/s10236-016-1009-0

Staneva, J., Wahle, K., Günther, H., and Stanev, E. (2016a). Coupling of wave and circulation models in coastal–ocean predicting systems: a case study for the German Bight. *Ocean Sci.* 12, 797–806. doi: 10.5194/os-12-797-2016

Staneva, J., Wahle, K., Koch, W., Behrens, A., Fenoglio-Marc, L., and Stanev, E. V. (2016b). Coastal flooding: impact of waves on storm surge during extremes – a case study for the German Bight. *Nat. Hazards Earth Syst. Sci.* 16, 2373–2389. doi: 10.5194/nhess-16-2373-2016

Stopa, J. E., Ardhuin, F., and Girard-Ardhuin, F. (2016). Wave climate in the arctic 1992-2014: seasonality and trends. *Cryosphere* 10, 1605–1629. doi: 10.5194/tc-10-1605-2016

Stouffer, R. J., Yin, J., Gregory, J. M., Dixon, K. W., Spelman, M. J., Hurlin, W., et al. (2006). Investigating the causes of the response of the thermohaline circulation to past and future climate changes. *J. Clim.* 19, 1365–1387. doi: 10.1175/JCLI3689.1

Suzuki, T., Hasumi, H., Sakamoto, T. T., Nishimura, T., Abe-Ouchi, A., Segawa, T., et al. (2005). Projection of future sea level and its variability in a high-resolution climate model: Ocean processes and Greenland and Antarctic ice-melt contributions. *Geophys. Res. Lett.* 32:L19706. doi: 10.1029/2005GL023677

Sweet, W. V., and Park, J. (2014). From the extreme to the mean: acceleration and tipping points of coastal inundation from sea level rise. *Earth's Future* 2, 579–600. doi: 10.1002/2014EF000272

Sztobryn, M. (2003). Forecast of storm surge by means of artificial neural network. *J. Sea Res.* 49, 317–322. doi: 10.1016/S1385-1101(03)00024-8

Talke, S. A., Orton, P., and Jay, D. A. (2014). Increasing storm tides in New York Harbor, 1844–2013. *Geophys. Res. Lett.* 41, 3149–3155. doi: 10.1002/2014GL059574

Tandeo, P., Autret, E., Chapron, B., Fablet, R., and Garello, R. (2014). SST spatial anisotropic covariances from METOP-AVHRR data. *Remote Sens. Environ.* 141, 144–148. doi: 10.1016/j.rse.2013.10.024

Testut, L., Wöppelmann, G., Simon, B., and Téchiné, P. (2006). The sea level at Port-aux-Français, Kerguelen Island, from 1949 to the present. *Ocean Dyn.* 56, 464–472. doi: 10.1007/s10236-005-0056-8

Thompson, P. R., Merrifield, M. A., Wells, J. R., and Chang, C. M. (2014). Wind-driven coastal sea level variability in the Northeast Pacific. *J. Clim.* 27, 4733–4751. doi: 10.1175/JCLI-D-13-00225.1

Thompson, P. R., and Mitchum, G. T. (2014). Coherent sea level variability on the North Atlantic western boundary. *J. Geophys. Res. Oceans* 119, 5676–5689. doi: 10.1002/2014JC009999

Tonani, M., Balmaseda, M., Bertino, L., Blockley, E., Brassington, G., Davidson, F., et al. (2015). Status and future of global and regional ocean prediction systems. *J. Operat. Oceanogr.* 8, s201–s220. doi: 10.1080/1755876X.2015.1049892

Usui, N., Fujii, Y., Sakamoto, K., and Kamachi, M. (2015). Development of a four-dimensional variational assimilation system for coastal data assimilation around Japan. *Mon. Weather Rev.* 143, 3874–3892. doi: 10.1175/MWR-D-14-00326.1

Verrier, S., Le Traon, P.-Y., Remy, E., and Lellouche, J.-M. (2018). Assessing the impact of SAR altimetry for global ocean analysis and forecasting. *J. Operat. Oceanogr.* 11, 82–86. doi: 10.1080/1755876X.2018.1505028

Vignudelli, S., Kostianoy, A. G., Cipollini, P., and Benveniste, J. (eds). (2011). *Coastal Altimetry*. Berlin: Springer, 578. doi: 10.1007/978-3-642-12796-0

Vilibić, I., and Šepić, J. (2017). Global mapping of nonseismic sea level oscillations at tsunami timescales. *Sci. Rep.* 7:40818. doi: 10.1038/srep40818

Vinogradov, S. V., and Ponte, R. M. (2011). Low-frequency variability in coastal sea level from tide gauges and altimetry. *J. Geophys. Res.* 116:C07006. doi: 10.1029/2011JC007034

Vitousek, S., Barnard, P. L., Fletcher, C. H., Frazer, N., Erikson, L., and Storlazzi, C. D. (2017). Doubling of coastal flooding frequency within decades due to sea-level rise. *Sci. Rep.* 7:1399. doi: 10.1038/s41598-017-01362-7

Vizcaíno, M., Lipscomb, W. H., Sacks, W. J., van Angelen, J. H., Wouters, B., and van den Broeke, M. R. (2013). Greenland surface mass balance as simulated by the Community Earth System Model. Part I: model evaluation and 1850–2005 results. *J. Clim.* 26, 7793–7812. doi: 10.1175/JCLI-D-12-00615.1

Vousdoukas, M. I., Mentaschi, L., Voukouvalas, E., Verlaan, M., Jevrejeva, S., Jackson, L. P., et al. (2018). Global probabilistic projections of extreme sea levels show intensification of coastal flood hazard. *Nat. Commun.* 9:2360. doi: 10.1038/s41467-018-04692-w

Warner, J. C., Defne, Z., Haas, K., and Arango, H. G. (2013). A wetting and drying scheme for ROMS. *Comput. Geosci.* 58:54–61. doi: 10.1016/j.cageo.2013.05.004

White, N. J., Church, J. A., and Gregory, J. M. (2005). Coastal and global averaged sea level rise for 1950 to 2000. *Geophys. Res. Lett.* 32:L01601. doi: 10.1029/2004GL021391

White, N. J., Haigh, I. D., Church, J. A., Koen, T., Watson, C. S., Pritchard, T. R., et al. (2014). Australian sea levels - Trends, regional variability and influencing factors. *Earth Sci. Rev.* 136, 155–174. doi: 10.1016/j.earscirev.2014.05.011

Widlansky, M. J., Marra, J. J., Chowdhury, M. R., Stephens, S. A., Miles, E. R., and Fauchereau, N. (2017). Multimodel ensemble sea level forecasts for tropical Pacific islands. *J. Appl. Meteorol. Climatol.* 56, 849–862. doi: 10.1175/JAMC-D-16-0284.1

Wijeratne, E. M. S., Woodworth, P. L., and Stepanov, V. N. (2008). The seasonal cycle of sea level in Sri Lanka and Southern India. *Western Indian Ocean J. Mar. Sci.* 7, 29–43. doi: 10.4314/wiojms.v7i1.48252

Williams, J., and Hughes, C. W. (2013). The coherence of small island sea level with the wider ocean: a model study. *Ocean Sci.* 9, 111–119. doi: 10.5194/os-9-111-2013

Wise, A., Hughes, C. W., and Polton, J. (2018). Bathymetric influence on the coastal sea level response to ocean gyres at western boundaries. *J. Phys. Oceanogr.* 48, 2949–2969. doi: 10.1175/JPO-D-18-0007.1

Woodworth, P. L., Aman, A., and Aarup, T. (2007). Sea level monitoring in Africa. *Afr. J. Mar. Sci.* 29, 321–330. doi: 10.2989/AJMS.2007.29.3.2.332

Woodworth, P. L., Hunter, J. R., Marcos, M., Caldwell, P., Menéndez, M., and Haigh, I. (2017a). Towards a global higher-frequency sea level data set. *Geosci. Data J.* 3, 50–59. doi: 10.1002/gdj3.42

Woodworth, P. L., Wöppelmann, G., Marcos, M., Gravelle, M., and Bingley, R. M. (2017b). Why we must tie satellite positioning to tide gauge data. *Eos Trans. Am. Geophys. Union* 98, 13–15. doi: 10.1029/2017EO064037

Woodworth, P. L., Melet, A., Marcos, M., Ray, R. D., Wöppelmann, G., Sasaki, Y. N., et al. (2019). Forcing factors causing sea level changes at the coast. *Surv. Geophys.* doi: 10.1007/s10712-019-09531-1

Woodworth, P. L., Pugh, D. T., and Bingley, R. M. (2010). Long-term and recent changes in sea level in the Falkland Islands. *J. Geophys. Res.* 115:C09025. doi: 10.1029/2010JC006113

Wöppelmann, G., and Marcos, M. (2016). Vertical land motion as a key to understanding sea level change and variability. *Rev. Geophys.* 54, 64–92. doi: 10.1002/2015RG000502

Wöppelmann, G., Marcos, M., Coulomb, A., Martín Míguez, B., Bonnetain, P., Boucher, C., et al. (2014). Rescue of the historical sea level record of Marseille (France) from 1885 to 1988 and its extension back to 1849–1851. *J. Geod.* 88, 869–885. doi: 10.1007/s00190-014-0728-6

Yang, J., Lin, X., and Wu, D. (2013). Wind-driven exchanges between two basins: some topographic and latitudinal effects. *J. Geophys. Res. Oceans* 118, 4585–4599. doi: 10.1002/jgrc.20333

Yin, J. (2012). Century to multi-century sea level rise projections from CMIP5 models. *Geophys. Res. Lett.* 39:L17709. doi: 10.1029/2012GL052947

Yin, J., and Goddard, P. B. (2013). Oceanic control of sea level rise patterns along the East Coast of the United States. *Geophys. Res. Lett.* 40, 5514–5520. doi: 10.1002/2013GL057992

Yin, J., Schlesinger, M., and Stouffer, R. J. (2009). Model projections of rapid sea-level rise on the northeast coast of the United States. *Nat. Geosci.* 2, 262–266. doi: 10.1038/NGEO462

Zanna, L., Brankart, J. M., Huber, M., Leroux, S., Penduff, T., and Williams, P. D. (2018). Uncertainty and scale interactions in ocean ensembles: from seasonal forecasts to multi-decadal climate predictions. *Q. J. R. Meteorol. Soc.* 1–16. doi: 10.1002/qj.3397

Zhang, X., Church, J. A., Monselesan, D., and McInnes, K. L. (2017). Sea level projections for the Australian region in the 21st century. *Geophys. Res. Lett.* 44, 8481–8491. doi: 10.1002/2017GL074176

Zhang, X., Oke, P. R., Feng, M., Chamberlain, M. A., Church, J. A., Monselesan, D., et al. (2016). A near-global eddy-resolving OGCM for climate studies. *Geosci. Model Dev. Discuss* 2016, 1–52. doi: 10.5194/gmd-2016-17

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REVIEW
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Integrated Observations of Global Surface Winds, Currents, and Waves: Requirements and Challenges for the Next Decade

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Ocean surface winds, currents, and waves play a crucial role in exchanges of momentum, energy, heat, freshwater, gases, and other tracers between the ocean, atmosphere, and ice. Despite surface waves being strongly coupled to the upper ocean circulation and the overlying atmosphere, efforts to improve ocean, atmospheric, and wave observations and models have evolved somewhat independently. From an observational point of view, community efforts to bridge this gap have led to proposals for satellite Doppler oceanography mission concepts, which could provide unprecedented measurements of absolute surface velocity and directional wave spectrum at global scales. This paper reviews the present state of observations of surface winds, currents, and waves, and it outlines observational gaps that limit our current understanding of coupled processes that happen at the air-sea-ice interface. A significant challenge for the coming decade of wind, current, and wave observations will come in combining and interpreting measurements from (a) wave-buoys and high-frequency radars in coastal regions, (b) surface drifters and wave-enabled drifters in the open-ocean, marginal ice zones, and wave-current interaction "hot-spots," and (c) simultaneous measurements of absolute surface currents, ocean surface wind vector, and directional wave spectrum from Doppler satellite sensors.

Keywords: air-sea interactions, Doppler oceanography from space, surface waves, absolute surface velocity, ocean surface winds

1. INTRODUCTION

The Earth's climate is regulated by the energetic balance between ocean, atmosphere, ice, and land. This balance is driven by processes that couple the component systems in a multitude of complex interactions that happen at the boundaries. In particular, the marine atmospheric boundary layer provides a conduit for the ocean and the atmosphere to constantly exchange information in the form of fluxes of energy, momentum, heat, freshwater, gases, and other tracers (**Figure 1**). These fluxes are strongly modulated by interactions between surface winds, currents, and waves; thus, improved understanding and representation of air-sea interactions demand a combined cross-boundary approach that can only be achieved through integrated observations and modeling of ocean winds, surface currents, and ocean surface waves.

Surface winds, currents, and waves interact over a broad range of spatial and temporal scales, ranging from centimeters to global scales and from seconds to decades (**Figure 2**). At present, there are fundamental gaps in the observations of these variables. For example, high-resolution satellite observations of ocean color and sea surface temperature reveal an abundance of ocean fronts, vortices, and filaments at scales below 10 km, but measurements of ocean surface dynamics at these scales are rare (McWilliams, 2016). Recent findings based on airborne measurements (Romero et al., 2017), numerical models (Ardhuin et al., 2017a), and satellite altimeter data (Quilfen et al., 2018) have shown that the variability of significant wave height at scales shorter than 100 km is dominated by wave-current interactions. Yet, the observational evidence from altimetry that supports that idea is limited to wavelengths longer than 50 km, due to signal-to-noise limitations of present satellite altimeters and tracking techniques that are not specifically optimized to estimate significant wave heights. Another notable observational gap lies in coastal, shelf, and marginal ice zones (MIZs), regions that control important exchanges between land, ocean, atmosphere, and cryosphere and are particularly relevant for society. Over one-fourth of the world's population lives in coastal areas (Nicholls and Cazenave, 2010; Wong et al., 2014) and could be impacted by processes resulting from wind-current-wave interactions, such as beach erosion, extreme sea level events, and dispersion of pollutants or pathogens. Unraveling these interactions to guide adaptation and mitigation strategies and increase resilience to natural hazards and environmental change calls for high spatial resolution and synoptic observations of total ocean surface current vectors, winds, and waves that will enable the development of improved model parameterizations, improved model representations of air-sea interactions, and improved forecasts and predictions.

Community efforts to fill the observational gaps for combined wind, current, and wave measurements have led to several recent proposals for new Doppler oceanography satellite concepts, such as the Sea surface KInematics Multiscale monitoring satellite mission, SKIM the Winds and Currents Mission, WaCM; and the SEASTAR mission. These missions propose to deliver a variety of simultaneous measurements of absolute surface velocity vector, Stokes drift, directional wave spectrum, and ocean surface wind vector. But although SKIM, WaCM, and SEASTAR share the common goal of measuring coupled air-sea variables simultaneously, each mission is intrinsically different, driven by different objectives, and targeting specific processes at different scales as enabled by the capabilities of their different technological solutions. Thus, the focus for WaCM lies in global monitoring of surface currents at scales comparable to scatterometer winds (∼30 km) and temporal scales of one to several days, seeking to better observe wind-current interactions and their impact on global surface fluxes. In turn, SKIM's objectives include the exploration of global mesoscale surface currents and their impact on heat, carbon and freshwater budgets from the equator (where they are not observed today), to high latitudes including the emerging Arctic (which is poorly sampled by altimeters). SKIM also promises to explore intense currents and associated extreme waves by measuring the total current vector together with the directional spectrum of the wave field, at medium-resolution and covering 99% of the world ocean, on average once every 4 days. Finally, at the high spatial resolution end of the spectrum, SEASTAR focuses on ocean submesoscale dynamics and complex processes in coastal, shelf and polar seas. SEASTAR would provide a two-dimensional synoptic imaging capability for total surface current vectors and wind vectors at ∼1 km resolution supported by coincident directional wave spectra. The key scientific drivers for SEASTAR are to deliver high-accuracy observations of the two-dimensional surface flow field and atmospheric forcing to understand processes linked to frontogenesis and upper ocean mixing that determine the vertical structure of the upper ocean. This includes observing the generation of strong vertical velocities and the fast and efficient transfer of heat, gases and energy from the air-sea interface

Abbreviations: 2D, two-dimensional; ADCP, Acoustic Doppler current profiler; AMRS-2, Advanced Microwave Scanning Radiometers; ASCAT, Advanced Scatterometer; ATI, Along-Track Interferometry; CCMP, Cross-Calibrated Multi-Platform ocean surface wind velocity product; CCS, California Current System; CFOSAT, China-France Oceanography SATellite; CMEMS, Copernicus Marine Environment Monitoring Service; CO_2, carbon dioxide; CYGNSS, NASA Cyclone Global Navigation Satellite System; DC, Doppler centroid; EKE, eddy kinetic energy; ERS-1/2, European Remote Sensing-1/2; ESA, European Space Agency; EUMETSAT, European Organization for the Exploitation of Meteorological Satellites; GDP, Global Drifter Program; GEKCO, Geostrophic and Ekman Current Observatory; GLAD, Grand Lagrangian Deployment; GNSS-R, Global Navigation Satellite System-Reflectometry; GNSS, Global Navigation Satellite System; GOCE, Gravity field and Ocean Circulation Experiment; GPM, Global Precipitation Measurement; GPS, Global Positioning System; HFR, high-frequency radars; LASER, Lagrangian Submesoscale Experiment; LES, Large Eddy Simulations; MDT, Mean Dynamic Topography; MIZ, Marginal Ice Zone; MSS, mean sea surface; NDBC, US National Data Buoy Center; NOAA, National Oceanic and Atmospheric Administration; NRT, Near Real Time; NSCAT, NASA Scatterometer; NWP, Numerical weather prediction; OSBL, ocean surface boundary layer; OSCAR, Ocean Surface Current Analysis Real-time; PIRATA, Prediction and Research Moored Array in the Tropical Atlantic; QuickSCAT, Quick Scatterometer; RAMA, Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction; RFI, Radio Frequency Interference; RMSE, Root Mean Square Error; RMS, Root Mean Square; RapidScat, International Space Station Rapid Scatterometer; SAR, Synthetic aperture radar; SEASAT, first satellite carrying a SAR; SKIM, Sea surface KInematics Multiscale monitoring satellite mission; SLA, Sea Level Anomalies; SSH, Sea Surface Height; SST, Sea Surface Temperature; SWOT, Surface Water and Ocean Topography; TAO, Tropical Atmosphere Ocean project; TRITON, Triangle Trans-Ocean Buoy Network; WaCM, Winds and Currents Mission.

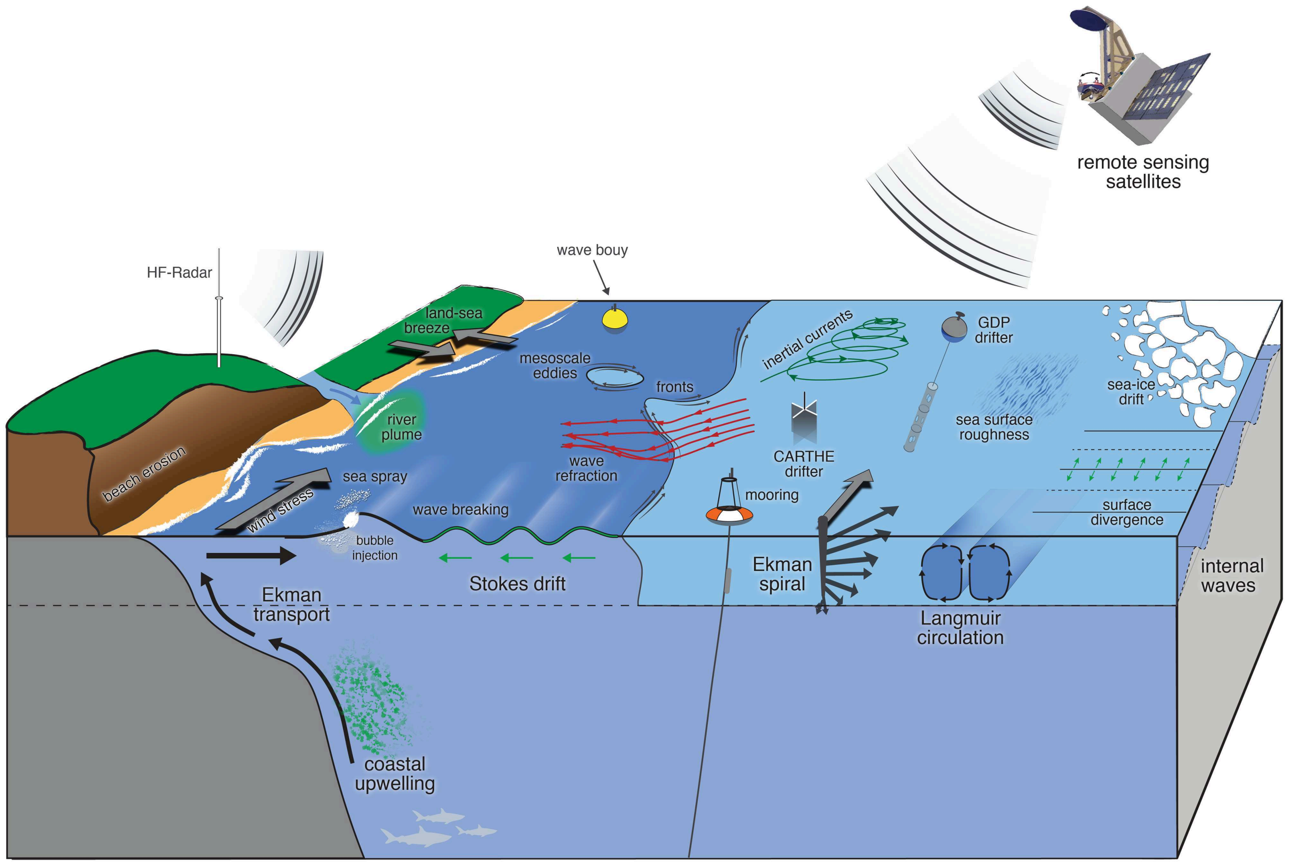

FIGURE 1 | Schematic representation of upper-ocean processes that are coupled through the interaction between surface winds, currents, and waves. Processes that are driven by these interactions range from regional to global scales and happen in coastal areas (e.g., coastal upwelling and land-sea breeze), open ocean (e.g., inertial currents and mesoscale eddies), and marginal ice-zones (e.g., sea ice drift). Multiple components of the observing system including *in situ* (e.g., surface drifters, wave buoys, and moorings) and remote sensing (e.g., HF-radar and satellites) platforms are also illustrated.

into the ocean interior, with the ultimate aim of developing improved parameterizations of these processes for operational monitoring and Earth system models used for predicting future climate.

In this context, a significant challenge for the next decade will be to combine and interpret measurements of wind, currents, and waves from existing *in situ* and remote sensing observational platforms with new measurements from future Doppler oceanography satellites, in a modeling framework that constantly evolves toward finer spatial and temporal resolutions and increasingly complex coupled systems. In this paper, we review the present status of wind, current, and wave observations as well as existing platforms and their respective limitations, with an emphasis on remote sensing techniques (section 2). Then, we discuss the scientific community requirements for observations of these variables in the context of physical processes that happen at the ocean-atmosphere interface (section 3). Lastly, we explore the opportunities for better observations of surface winds, currents, and waves, as proposed by possible future Doppler oceanography from space missions (section 4). A summary and recommendations are presented in section 5.

2. PRESENT STATE AND LIMITATIONS OF WIND, CURRENT, AND WAVE OBSERVATIONS

During the past few decades, the oceanographic community has been trying to overcome the issue of sparse and heterogeneous measurements by adapting existing technology, applying novel data analysis techniques and processing tools, and combining observations from multiple sensors, with efforts to achieve higher resolution in space and time. For example, high-resolution imagery from synthetic aperture radars (SAR) and optical sensors onboard of satellites have been successfully used to study wind-current-wave interactions in specific regions (e.g., Rascle et al., 2016, 2017; Kudryavtsev et al., 2017), but these results have not yet led to the routine production of data. Significant scientific progress has been enabled by products, such as the Ocean Surface Current Analysis Real-time (OSCAR, Bonjean and Lagerloef, 2002), GlobCurrent (Rio et al., 2014), and the Cross-Calibrated Multi-Platform ocean surface wind velocity product (CCMP, Atlas et al., 2011); however, observational gaps in measurements of winds, currents, and waves still remain. Many components

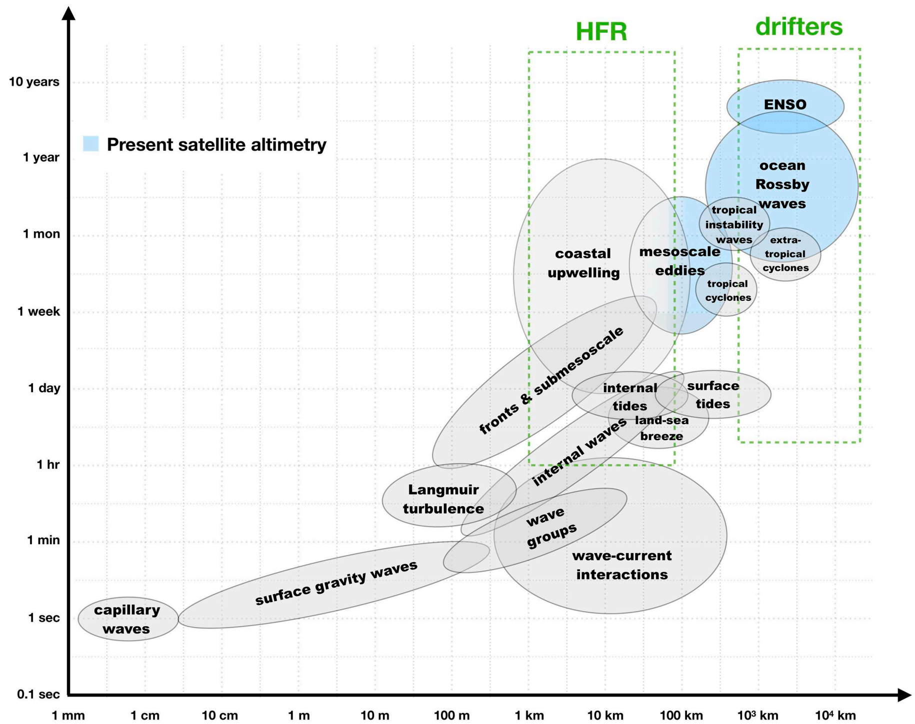

FIGURE 2 | Spatial and temporal scales of multiple ocean and atmosphere process [courtesy of Dudley Chelton, adapted from Chelton (2001)]. Processes that can be observed by the present constellation of altimeters are shaded in blue. The square green boxes delimit the approximate range of scales that can be captured by high-frequency radars (HFR) and drifters from the Global Drifter Program.

of the current observing system for surface winds (e.g., surface buoys and satellites), currents (e.g., HF-radar, surface drifters, and moorings), and waves (e.g., wave buoys) are illustrated in **Figure 1**. Below we discuss applications and limitations of each specific component.

2.1. Surface Winds

2.1.1. *In situ* Measurements

Measurements of surface winds over the ocean from weather ships and later from buoys began after World War II, motivated by the development of the aviation industry. Meteorological measurements from surface buoys remain an important source of near-real-time wind data for weather and navigational applications, and they are increasingly important for developing and validating estimates of winds from satellite and land-based remote sensing (Bourassa et al., 2019). Buoys are important for remote sensing because they provide an absolute calibration reference for satellite wind retrievals (Wentz et al., 2017). The buoys most commonly used for validating satellite wind retrievals are the tropical moored buoy arrays (TAO/TRITON in the Pacific, the PIRATA array in the Atlantic, and the RAMA array in the Indian Ocean), the network of buoys maintained by the US National Data Buoy Center (NDBC), the handful of the National Oceanic and Atmospheric Administration (NOAA) Ocean Reference Station buoys, and the coastal buoys maintained by the Canadian Department of Fisheries and Oceans (Wentz et al., 2017).

2.1.2. Scatterometers and Radiometers

As the wind blows over the surface of the ocean, short waves with scales of centimeters are formed, giving rise to what we refer as sea surface roughness. Remote sensing of ocean surface winds relies on the relationship between the wind speed and direction and the sea surface roughness, which modulates reflective and emissive properties of the ocean surface at those scales. Over the past two decades, the two most common sensors used to measure surface winds from space are microwave radiometers and scatterometers. Below we present a short description of these two technologies. For a detailed review of remotely sensed winds including instrument specifications, the reader is referred to Bourassa et al. (2019).

Microwave radiometers are passive sensors that estimate the wind speed based on the spectrum of the microwave radiation emitted by the sea surface, which, among other things, is a function of the sea surface roughness. Present oceanography satellites with onboard radiometers (e.g., the Advanced Microwave Scanning Radiometers, AMRS-2; and the Global Precipitation Measurement, GPM) are capable of estimating the wind speed with spatial resolution of about 30 km and accuracy of up to 1 m s^{-1}; however, the quality of the wind speed measurements from this type of sensor is significantly degraded by the presence of rain (Meissner and Wentz, 2009). Another drawback of conventional microwave radiometers is that it is limited to measuring the surface wind only as a scalar quantity. Polarimetric microwave radiometers, such as WindSat, can be used to address this issue and retrieve the surface ocean vector wind, although the directional signal can be noisy for low wind speeds (< 7 m s^{-1}) leading to uncertainties in the wind direction that can be $>30°$ (Meissner and Wentz, 2005).

Scatterometers are active sensors that measure the fraction of energy from the radar pulse reflected back to the satellite, also known as backscatter. The backscatter is a function of the sea surface roughness, which is, in turn, a function of the wind speed and direction. The intensity of the backscatter for a given incidence angle determines the wind speed, while the wind direction is estimated by taking advantage of the fact that the measured backscatter is a function of the relative angle between the wind direction and the azimuth angle. The present constellation of scatterometers maps the surface wind field globally, with typical spatial resolution of 25 km and has been successfully used in weather forecasting applications (e.g., Atlas et al., 2001; Chelton et al., 2006), long-term climate studies (e.g., Halpern, 2002), and air-sea interactions (e.g., Xie et al., 1998; Chelton and Xie, 2010). The main limitations of scatterometers are contamination by rain (depending on the frequency of the transmitted signal), lack of data near the coast, and poor temporal sampling. Additionally, because of the way that backscatter depends on azimuth angle, possible wind directions can differ by 180°, which degrade the quality of the data. In rain-free conditions, wind directions (so-called ambiguities) are correctly identified more than 90% of the time; however, in or near rain events errors are more likely to occur. These problems can be reduced with antenna designs that obtain three or more looks at each location measured on the ocean surface (such the fan-beam design employed by NSCAT, ASCAT, and SCAT on board the China-France Oceanography SATellite, CFOSAT; and the rotating pencil-beam design used in QuickSCAT and RapidScat). Further improvements in the estimation of wind direction can be achieved by using Doppler directional information. Finer resolution would provide observations closer to the coast and better capture smaller-scale variability and derivative fields. Sufficiently small resolution (around 5 km) would allow scatterometers to see between rain features in hurricanes, and provide much greater utility in rain events. Temporal sampling could be improved with a mid-earth orbit or a synergetic constellation.

2.1.3. Synthetic Aperture Radars

Synthetic aperture radar (SAR) satellites are the only space system able to observe the ocean sea surface at day and night regardless of cloud coverage, with resolution of tens of meters and spatial coverage of hundreds of kilometers. Launched in 1978, SEASAT was the first satellite carrying a SAR (L-Band) together with a scatterometer (Ku-Band). Although originally designed for wave measurements, early comparisons demonstrated a strong correlation between the SEASAT SAR image intensity and SEASAT scatterometer wind speed (e.g., Weissman et al., 1979; Beal, 1980). Despite the short lifetime of SEASAT, the first analysis revealed some of the most interesting potential for SAR, such as its ability to monitor the ocean surface at high resolution under hurricanes (Fu and Holt, 1982) and the signature of the secondary atmospheric circulation in the marine atmospheric boundary layer (Brown, 1980, 1986). Gerling (1986) directly compared SAR wind speed and direction with scatterometer measurements, opening perspectives for high-resolution wind measurements from space.

Like existing scatterometers, SAR systems only measure the ocean surface backscattering in co-polarization (VV or HH). Taking advantage of accurate calibration with respect to SEASAT, algorithms were designed to provide a quantitative estimate of the wind speed and direction. Most of them rely on the so-called "scatterometry approach," as described in section 2.1.2. However, in contrast to scatterometers, SAR systems do not have multiple (e.g., ASCAT) or rotating (e.g., QuikSCAT) antennae but only a single antenna pointing across track. This limits how well the inverse problem can be constrained, as only a single measurement is available to infer both wind speed and direction, in contrast to the three or more measurements that can be combined in the inversion scheme for scatterometers.

Various techniques exist to retrieve the wind direction and wind speed from the SAR image intensity, such as image processing techniques (e.g., Koch, 2004) that use ancillary data (e.g., wind direction from buoys, scatterometers or numerical weather prediction models). Recent missions, such as Radarsat-2 and Envisat allowed retrieval techniques to be refined to consider weak wind speeds and better calibrated data (Zhang et al., 2011; Mouche and Chapron, 2015). When Applied to C-band SAR, the scatterometry approach currently results in ocean wind vector measurements with root mean squared errors of <2 m s^{-1} for wind speed and $<20°$ for wind direction.

The launch of Envisat and Radarsat-2 in the mid 2000s, opened a new area for SAR by providing the first evidence of a geophysical signature in the Doppler signal from a spaceborne SAR (Chapron et al., 2004, 2005). The relationship between wind waves and the Doppler from SAR allowed for inversion schemes that take advantage of the strong modulation of the Doppler with respect to wind direction in order to retrieve the surface wind vector (Mouche et al., 2012). The present generation of C-band SARs (e.g., Sentinel-1) have both co- and cross-polarization acquisition, which have recently been combined to retrieve ocean wind measurements in extreme conditions. These provide reliable wind measurements for maximum wind speeds of up to 60 m s^{-1} (Mouche et al., 2017). These results have attracted interest from outside of the SAR community. In particular, the high-sensitivity of the cross-polarization signal inspired future mission concepts (Fois et al., 2015), and EUMETSAT (European Organization for the Exploitation of Meteorological Satellites) together with ESA (European Space Agency) now plan to add a cross-polarized channel to the next generation of operational scatterometer missions (i.e., the next Polar System Second Generation) dedicated to the ocean surface wind measurement at medium resolution (Stoffelen et al., 2017). Other mission concepts (e.g., Ardhuin et al., 2018; Rodriguez, 2018; Gommenginger, 2019) also suggest relying on Doppler and radar backscatter measurements at multiple angles and targeting combined wind, waves, and current measurements.

Radarsat-2 and Envisat also allowed a new stage in the data acquisition by providing routine acquisitions over specific areas, yielding practical applications, such as the high-resolution wind

Atlas for Europe (Hasager et al., 2015), and scientific applications, such as the study of the marine atmospheric boundary layer rolls in hurricanes (Foster, 2005). However, the very high resolution of SAR makes the analysis of the signal challenging. Many geophysical phenomena other than wind can impact the scales of wind-waves. These phenomena include rain (Atlas, 1994; Alpers et al., 2016), oceanic fronts (Kudryavtsev et al., 2014b), internal waves (Fu and Holt, 1982), and waves-current interactions (Kudryavtsev et al., 2014b). In addition, SAR is often used in coastal areas where strong interactions with topography and bathymetry can occur and sometimes dominate the wind-induced signal. This also lends support for a new generation of algorithms relying on multiple radar quantities to jointly invert for several geophysical parameters rather than deriving each parameter through an independent strategy.

2.1.4. Global Navigation Satellite System-Reflectometry

Global Navigation Satellite System-Reflectometry (GNSS-R) is an innovative Earth observation technique that exploits signals of opportunity from Global Navigation Satellite System (GNSS) constellations after reflection on the Earth surface. In brief, navigation signals from GNSS transmitters, such as those of the Global Positioning System (GPS) or Galileo are forward scattered off the Earth's surface in the bistatic specular direction. Dedicated GNSS-R receivers on land, on airborne platforms, or on separate spaceborne platforms detect and cross-correlate the reflected signals with direct signals from the same GNSS transmitter to provide geophysical information about the reflecting surface. GNSS-R can provide geophysical information about numerous surface properties and has multiple applications in Earth observation, including remote sensing of ocean roughness, soil moisture, snow depth, and sea ice extent (e.g., Cardellach et al., 2011; Zavorotny et al., 2014).

The exploitation of GNSS signals for ocean wind and sea state monitoring is one of the earliest and most mature applications of GNSS-R (e.g., Hall and Cordey, 1988; Garrison et al., 1998; Clarizia et al., 2009; Foti et al., 2015; Ruf et al., 2016). One key advantage of GNSS-R is the passive nature of the receiving hardware, which enables the design of low mass, low-power, low-cost instruments that can be flown on constellations of small satellites (e.g., Unwin et al., 2013) or as payloads of opportunity on other platforms/missions. This potential for low-cost implementation provides the option to build a comparably affordable Earth observation system characterized by sensors on multiple satellites to achieve very high spatio-temporal sampling of surface geophysical parameters. This offers significant benefits when trying to observe fast-varying processes, such as surface winds, sea state and tropical cyclones. In addition, by operating in the L-band microwave frequency range, GNSS-R is much less affected by heavy precipitation than other spaceborne measurement techniques, such as scatterometry, which operates at higher microwave frequencies (e.g., Quilfen et al., 1998).

Significant progress has been made over the past 5 years to quantify the capabilities of spaceborne GNSS-R to measure ocean winds and sea state, thanks to two GNSS-R missions: the UK TechDemoSat-1 mission launched in July 2014 (Foti et al., 2015) and the NASA Cyclone Global Navigation Satellite System (CYGNSS) launched in December 2016 (Ruf et al., 2016). In both cases, reported retrieval performances for GNSS-R wind speeds are better than 2 m s^{-1} root mean squared error (RMSE) for winds from 3 to 20 m s^{-1}. In addition, GNSS-R observations from TechDemoSat-1 obtained in tropical cyclones indicate that spaceborne GNSS-R can depict fine-scale structures near the eye wall of hurricanes (Foti et al., 2017), thereby opening promising new opportunities as well as new challenges regarding the exploitation of GNSS-R to improve our understanding of hurricanes.

2.2. Surface Currents

2.2.1. Satellite Altimetry

Over the last 25 years, the most exploited system for the monitoring of ocean surface currents for ice-free global scale has been altimetry. This is due to the fact that the flow in the ocean interior (away from the boundary layers) and away from the equator is to leading order in geostrophic balance, which means that the ocean surface velocity field can be readily obtained from the gradients of the ocean dynamic topography (the sea level relative to the geoid). In ice-free conditions, altimetry provides global, accurate, and repeated measurements of the Sea Surface Height (SSH), which is the sea level above a reference ellipsoid and is made of two components: the geoid and the absolute dynamic topography. To cope with the lack of an accurate geoid at the spatial resolution of the altimeter measurements (a few kilometers along-track), altimeter measurements are time-averaged over a long time period (typically 20 years for the latest solutions). The resulting mean sea surface height (Andersen et al., 2016; Pujol et al., 2018) is removed from the instantaneous altimeter measurements to obtain measurements of the Sea Level Anomalies (SLA). Along-track SLA from multiple altimeter missions are combined to calculate gridded maps. The effective resolution of the SLA grid depends both on the number of satellites in the altimeter constellation and on the prescribed mapping scales. Analyzing the spatial coherence between the Copernicus Marine Environment Monitoring Service (CMEMS) altimeter maps and independent datasets, Ballarotta et al. (2019) found that multi-mission altimeter maps based on three satellites (available 70% of the time over the period 1993–2017) resolve mesoscale structures ranging from 100 km wavelength at high latitude to 800 km wavelength in the equatorial band over 4 weeks timescales.

A key reference surface needed to reconstruct the ocean dynamic topography from the sea level anomalies is the ocean Mean Dynamic Topography (MDT). The MDT is now known to centimeter accuracy at 100 km resolution through combined use of state-of-the-art mean sea surface (MSS) and GOCE (Gravity field and Ocean Circulation Experiment) data, at least in open ocean regions and away from coastal and ice-covered areas (Andersen et al., 2016). The use of additional information from *in-situ* oceanographic measurements (drifting buoy velocities and hydrographic profiles) allows the MDT to be refined to resolve scales down to 30–50 km (Maximenko et al., 2009; Rio et al., 2014; Rio and Santoleri, 2018). Effective resolution depends on the *in-situ* data density and is therefore not homogeneous (e.g., there are fewer *in situ* data at high latitudes and in coastal areas). Further developments are needed to increase the resolution of the MDT, in particular in the context of the upcoming SWOT mission, the primary objective of which is to characterize the ocean mesoscale and sub-mesoscale circulation with scales larger than 15 km. We refer the reader to Morrow et al. (2019) for a detailed description of the SWOT mission.

The first baroclinic Rossby radius in the ocean, which defines the expected spatial scales of geostrophic structures, ranges from 200 km at the equator to 10–20 km at high latitudes (Chelton et al., 1998; Nurser and Bacon, 2014). The mapping capability of the present altimeter constellation, coupled with the resolution and accuracy of the available MDT products, is not sufficient to resolve the full geostrophic flow at mid latitudes, and this is even worse at high latitudes. In addition, geostrophic currents are only one component of the total surface current in the ocean; other components include the Ekman currents, which are set up by a stationary wind field; tidal currents; and a number of other ageostrophic (i.e., not geostrophic) currents. In addition, the geostrophic approximation is not valid at the equator. At high latitudes, another limitation comes from the very coarse sampling of the ice-covered ocean where leads allow only a sparse view of the dynamic topography (Armitage et al., 2017), which particularly excludes the mesoscale, and the MIZs. The altimeter observing system, therefore, suffers from two major limitations in monitoring ocean surface currents: only the geostrophic component of the currents can be derived, and in some areas, only for a limited range of spatial scales.

In order to obtain more realistic ocean surface currents, corrections may be made to the altimeter-derived geostrophic currents. In ice-free oceans (Dotto et al., 2018), Ekman currents can be estimated, given knowledge of the wind field (Rio and Hernandez, 2003), and added to the geostrophic currents. Various global ocean surface current products are now available based on such an approach: the OSCAR product (Bonjean and Lagerloef, 2002), the Geostrophic and Ekman Current Observatory (GEKCO) product (Sudre et al., 2013), and the GlobCurrent product (Rio et al., 2014). **Figure 3** shows an example of the surface velocity field for December, 31st 2017 from the GlobCurrent product, which includes both altimetry-based geostrophic velocity and wind-derived Ekman currents. Alternatively, the spatial and temporal resolution of the altimeter-derived ocean surface currents may be enhanced by exploiting the synergy between altimetry and other satellite observations. A number of methods have been tested, including Maximum Cross Correlation (e.g., Bowen et al., 2002; Warren et al., 2016), the effective Surface Quasi Geostrophy framework (e.g., Isern-Fontanet et al., 2006; González-Haro et al., 2016), and inversion of the SST conservation equation (e.g., Vigan et al., 2000; Rio et al., 2016; Rio and Santoleri, 2018), as illustrated in **Figure 4**.

2.2.2. Surface Drifters

Surface drifters are semi-Lagrangian drifting buoys that approximately follow the current at the ocean surface and can be used in climate and oceanographic research. For over four decades, satellite-tracked surface drifters have been used to map near-surface currents in the global oceans (Lee and Centurioni, 2018) as part of the Global Drifter Program (GDP). Currently, an array of over 1,400 surface drifters is maintained through GDP, with the goal to keep an average drifter spacing of 5 degrees in the entire globe. However, sustaining the number of drifters in regions of predominantly divergent flows, such as the equatorial region, is difficult since the divergence of the surface flow results in a continuous drifter loss toward the subtropics.

Surface drifters from the GDP consist of surface drifting buoys that have an attached holey-sock drogue (sea anchor) centered at a depth of 15 m and are tracked mostly using the Argos positioning system (http://www.argos-system.org), but recently also using GPS (Elipot et al., 2016). Motions due to slip caused by windage, surface gravity wave rectification, and Stokes drift are major challenges for interpreting currents from surface drifters (Lumpkin et al., 2017). Even though the use of a drogue and careful design of the surface buoy can greatly reduce slip to 0.1% of the wind speed for 10-m winds of up to 10 m s^{-1}, the resulting velocity estimated from the drifter is still a combination of the direct wind-driven surface current, plus the slip, plus the integrated shear between the surface and the end of the drogue. Several methods for correcting for slip bias in both drogued and undrogued drifters have been proposed (e.g., Pazan and Niiler, 2001; Poulain et al., 2009) and have been recently updated by Laurindo et al. (2017). On average, GDP drifter position fixes are received every $\sim$1.2 h and can be used to estimate near-surface velocities by finite differencing consecutive fixes. The standard product distributed by GDP objectively interpolates velocities to regular 6-h intervals and has been used to map large-scale ocean currents (Lumpkin and Johnson, 2013), study pathways of marine debris (Maximenko et al., 2012), and improve satellite-based products (Rio et al., 2014). Taking advantage of improvements in the temporal sampling of the drifters since 2005, the GDP has recently developed an alternative drifter velocity product that distributes surface velocities at 1-h intervals. These higher-frequency velocities have the potential to be used to investigate inertial, tidal, and super-inertial motions (Elipot et al., 2016; Lumpkin et al., 2017).

The coarse and scattered distribution of drifters from the GDP limits their application to relatively large-scale processes. The development of low-cost, disposable, and biodegradable drifters (e.g., the CARTHE drifter) has allowed for large deployments of an unprecedented number of drifters ($O(10^3)$) capable of monitoring for the first time rapidly-evolving submesoscale ($<$10 km) motions as well as clustering and dispersion of floating particles. At these scales, surface convergences and divergences lead to abrupt changes in the concentration of floating materials, resulting in strong gradients that can have profound implications for oil spills, larval dispersion, and pathways of plastic debris (D'Asaro et al., 2018). While surface drift measurements from a few experiments, such as the Grand Lagrangian Deployment (GLAD) and the Lagrangian Submesoscale Experiment (LASER) have shed some light onto submesocale dynamics, a systematic means of monitoring the surface of the ocean at these scales is needed in order to bridge the gap between mesoscale and submesoscale processes and to improve model predictions in response to environmental disasters.

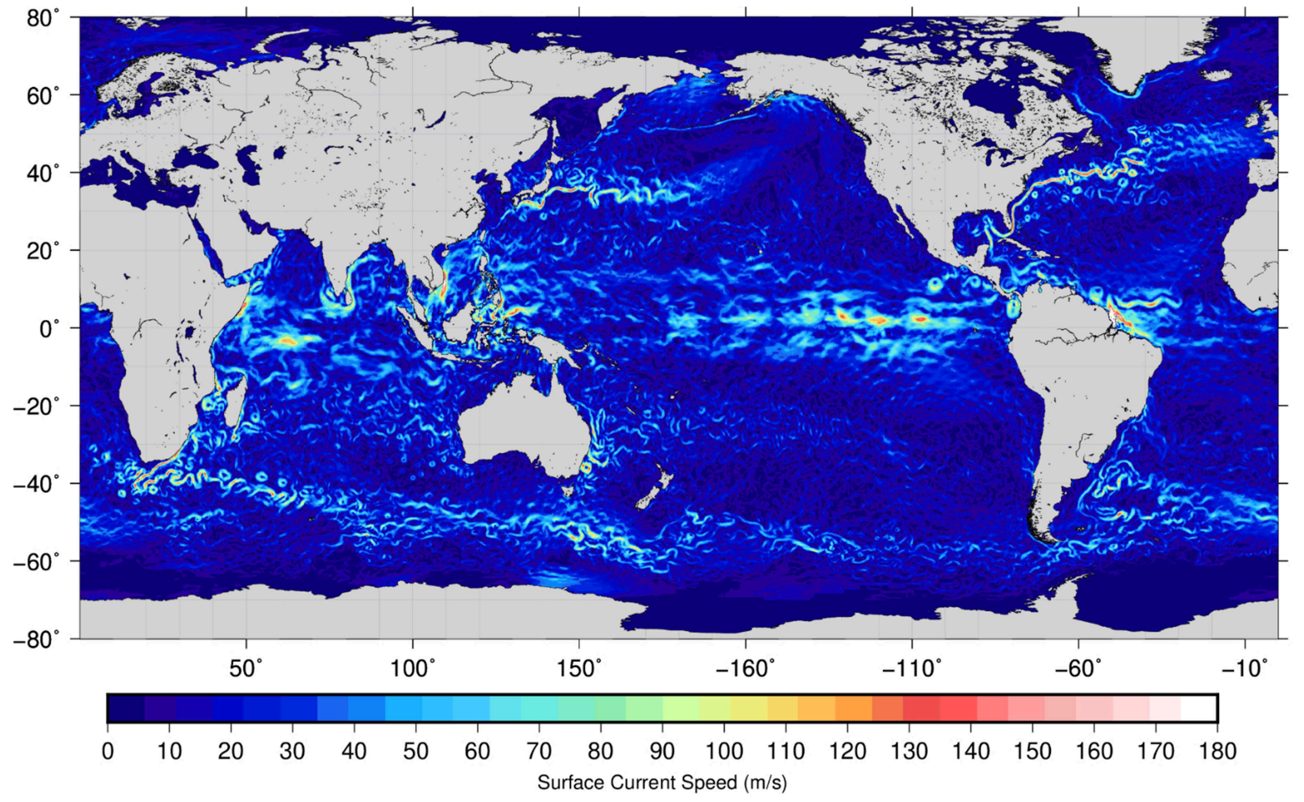

FIGURE 3 | Map of combined geostrophic and Ekman surface currents on December, 31st 2017 from the GlobCurrent project (Rio et al., 2014).

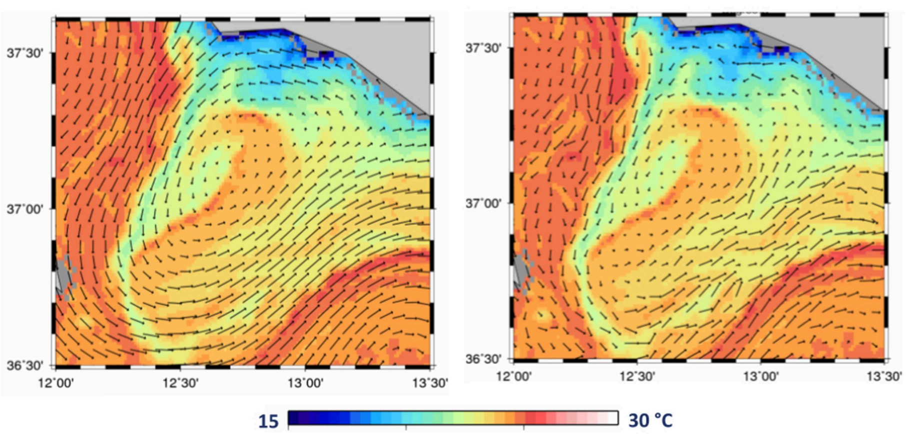

FIGURE 4 | Sea surface temperature (SST) in the Sicily channel (Mediterranean Sea) on July, 23rd 2016 from Sentinel-3 and ocean surface currents derived (left) from the Sentinel-3 altimeter data and (right) from the combination of the Sentinel-3 altimeter and SST information using the method described in Rio and Santoleri (2018).

2.2.3. High Frequency Radar

Shore-based high-frequency radars (HFR), which provide measurements of surface currents, are important components of coastal observing systems. HFRs transmit radio signals (3–45 MHz) and make use of Bragg resonant reflection from wind-driven surface gravity waves, in combination with the dispersion relationship, to derive surface currents from the Doppler shift in the returned signal (Crombie, 1955; Barrick et al., 1977). Operational networks of HFRs provide near real-time measurements of surface current fields with 0.5–6 km horizontal and 1-h temporal resolution for distances extending to 300 km offshore. Data from these systems support both scientific and operational efforts, including oil spill response, water quality and pollution tracking studies, fisheries research, maritime domain awareness, search and rescue, and adaptive sampling (Terrill et al., 2006; Harlan et al., 2010).

HFR derived surface currents have been used in a wide variety of scientific studies (see Paduan and Washburn, 2013) to map tidal currents, eddies, wind and buoyancy-driven currents, and for model validation and data assimilation. Kim et al. (2011) used 2 years of data from the US West Coast HFR network to capture various scales of oceanic variability, including the existence of poleward propagating wave-like signals along the US coastline presumably associated with coastal-trapped waves. Wavenumber (k) spectra of measured currents show a k^{-2} decay at scales smaller than 100 km, consistent with theoretical submesoscale spectra (McWilliams, 1985). HFR spatial resolution is generally higher than satellite altimeters, providing unique insight into submesoscale variability in the coastal zone. Marine ecological studies have used HFR systems to map harmful algal blooms (Anderson et al., 2006) and larval transport pathways (e.g., Gawarkiewicz et al., 2007), tying the biological response to the physical environment.

HFR is susceptible to external Radio Frequency Interference (RFI), which has been mitigated in recent years by international adoption by the radio community of set aside bands for oceanographic applications. While HFR for oceanography can span 3–45 MHz, at lower frequencies (typically below 8 MHz), HFR can be impacted by interference from diurnal variations in the ionosphere, which result in higher noise levels as a result of long-range propagation conditions. Within embayments, such as San Francisco Bay, HFRs have been shown to be effective when operated at the higher frequency bands, due to the availability of short period Bragg waves. The radar systems require ongoing maintenance and recalibration of antenna patterns due to seasonal changes in surrounding vegetation and other effects (Cook et al., 2008). HFR has also been used to measure components of the surface wave field due to the second order backscatter effects in the Doppler spectrum. However, this technique has not been shown to provide the same level of fidelity as *in-situ* measurements or imaging style radars that operate at X-band. An in-depth review on HFR can be found in Roarty et al. (2019).

2.2.4. Moorings

One direct approach to measuring ocean currents is to install current meters or current profilers on a mooring line that runs between an anchor on the seafloor and a flotation buoy. If the flotation buoy is on the surface, it is a "surface mooring," and, if the buoy is beneath the surface, it is a "subsurface mooring." Early current meters measured current speed by measuring the revolutions of a propeller or rotor (e.g., Weller and Davis, 1980), but almost all modern "*in situ*" ocean velocity measurements use acoustic techniques relying on measurement of acoustic travel times or Doppler shifts. Acoustic Doppler current profilers (ADCPs) allow measurement of velocity profiles and are now one of the most commonly used instruments for measuring ocean currents *in situ*. A great advantage of moored velocity measurements is that they can provide very good temporal resolution, with a typical temporal resolution of 1 h for a 1-year record.

The near-surface environment is challenging because of the action of surface waves and biofouling. The surface waves cause physical heaving and strong, oscillatory wave-driven flow past the instruments, which can cause: (1) mechanical damage to the mooring and instruments, (2) flow-distortion errors (e.g., from flow separation near the buoy or instrument), (3) sampling errors (e.g., from aliasing of the wave orbital velocity), and (4) difficulties in interpretation because the instruments heave up and down in a surface-following reference frame (which is a mix of Eulerian and Lagrangian reference frames and consequently causes partial contamination of the mean velocity by the Stokes drift (Pollard, 1973). Although there are many oceanographic surface moorings, most of these moorings do not measure near-surface ocean currents. There are only a handful of moored records of open-ocean currents taken in the upper 10 m of the ocean. The records that do exist should be used with caution because of the challenges listed above.

2.2.5. Sea Ice Drift

Finally, a special case of surface currents is the drift of sea ice. Different methods probe different parts of the spatiotemporal spectrum. Buoys drifting with the sea ice (Rampal et al., 2011; Gimbert et al., 2012) provide a very high sampling rate but offer a very local sampling of the sea ice cover. On the other hand, image correlation techniques from passive microwave sensors (Tschudi et al., 2016) or SAR (Kwok et al., 1998) offer a pan-Arctic view of the deformation features of the sea ice but are limited to coarser length scales of deformation, typically larger than 10 km for passive microwave and 1 km for SAR imagery and to daily to monthly timescales (for more recent reviews see Sumata et al., 2015; Muckenhuber and Sandven, 2017). Doppler shift analysis techniques (Chapron et al., 2005) provide near instantaneous (sub-hourly) surface displacements but offer sparse spatial sampling that limits measurements to one component of the ice drift (Kræmer et al., 2018). Finally, recent results (Oikkonen et al., 2017) using correlation of ship-based radar images offer a sub-kilometric view of sea ice kinematics at timescales down to tens of seconds but are inherently limited in space and time to icebreaker routes. In this context the new rotating multibeam Doppler SAR technology on board the proposed SKIM ESA explorer mission will complement existing techniques and in particular will expand on the existing delay-Doppler products by resolving the second component of the sea ice drift vector at a near instantaneous frequency and kilometric resolution with a daily coverage over most of the Arctic (Ardhuin et al., 2018).

2.3. Surface Waves

2.3.1. Wave Buoys and Wave-Enabled Drifting Buoys

The majority of historical wave measurements have been collected from moored sensors near coastlines with limited spatiotemporal information about the wave field offshore. In general, high-seas wave observations are sparsely collected from ship observations or from satellites, which have long duration repeat intervals. Moored buoys use heave-pitch-roll sensors, accelerometers, or displacement sensors to measure orthogonal components of some combination of the surface wave kinematics, and they invert these data for the first five directional moments at each frequency (Longuet-Higgins et al., 1963), which can be used to obtain an estimate of the wave directional spectrum using statistical methods (e.g., Lygre and Krogstad, 1986). To eliminate the cost and effort of maintaining moored buoys, a growing number of small-form-factor, easily deployable surface drifters (Veeramony et al., 2014; Centurioni et al., 2017) with high fidelity wave measurements have been developed for remote and under-sampled regions of the global ocean.

Drifting wave buoys use GPS signals from a single GPS receiver to measure horizontal and vertical velocities (De Vries et al., 2003). The three-axis GPS velocity data are used to obtain wave displacement spectra in a manner similar to the more traditional buoy technology referred to above. Wave measurements from these cost-effective and compact counterparts to the moored wave buoys have been shown to compare well with traditional accelerometer methods (Colbert, 2010; Herbers et al., 2012). Applications of these drifting buoys include wave attenuation in ice (Doble and Bidlot, 2013; Doble et al., 2017; Sutherland and Dumont, 2018), targeted sampling under storm tracks, wave-current interactions (Zippel and Thomson, 2017; Veras Guimarães et al., 2018), and wave observations on high seas where mooring buoys are technically challenging and costly. For detailed characteristics of *in situ* wave measurements, we refer the reader to Ardhuin et al. (2019).

2.3.2. Satellite Remote Sensing

In contrast to the point measurements provided by buoys, remote sensing satellites provide a unique global view of the ocean that is capable of sampling the most extreme conditions, for which no buoy record is available. Currently, the most robust satellite-based measurement of the sea state is the significant wave height (H_s) derived from satellite altimeter waveforms as a byproduct of the SSH processing. Since measurements of H_s are not the primary goal of present altimeters, their sensors are not optimized for measuring the sea state, and the first step one typically goes through when using standard altimetric products is to smooth out the noise by averaging H_s values along-track over a distance of the order of 50 km. In addition to being relevant to the wave community, altimeter measurements of H_s are also an important parameter for estimating and correcting the sea state bias in the SSH measurements (Fu and Glazman, 1991). Because of their global sampling, altimeters are uniquely capable of measuring the most extreme sea states: the highest H_s value ever recorded in a 1-Hz product is 20.1 m (Hanafin et al., 2012). At the other extreme, altimeters have difficulty resolving wave heights below 1 m (e.g., Sepulveda et al., 2015). Altimeters also provide a back-scatter power that, when well-calibrated, can be used to estimate the mean square slope of the sea surface (Jackson et al., 1992; Nouguier et al., 2016).

More information on the sea state, in particular, the direction, wavelength, and energy of swells can be obtained from high-resolution imagery of the ocean. The most common form of wave measurement from imagery uses the specially designed "wave mode" of SARs on ESA satellites ERS-1/2, Envisat, and Sentinel 1 (Hasselmann et al., 2013). This wave mode is particularly well-suited for the routine tracking of swell fields across the oceans (Collard et al., 2009). Unfortunately, it is unable to detect the part of the wave spectrum associated with shorter wind waves, due to the blurring of the SAR image by the wave orbital velocities; the orbital velocities can still be estimated by statistical methods, albeit with limited accuracy (Li et al., 2011). This "cut-off" between the resolved and blurred part of the spectrum is strongest in the azimuth (along-track) direction and is a function of the sea state. Waves traveling in the azimuth direction with wavelengths shorter than 100 m can only be measured in quiet conditions or ice-covered oceans (Ardhuin et al., 2017b). In fact, SARs are the only satellite systems that have been proven to measure wave heights in ice-covered regions. Other types of radars (e.g., wave scatterometers) do not use SAR processing and provide 1D spectra along the line of sight of a rotating beam that can be combined to produce a 2D spectrum (Jackson et al., 1992; Caudal et al., 2014). The first space-borne wave scatterometer, the China-France Ocean Satellite mission (CFOSAT), was recently launched on October, 2018 (Hauser et al., 2017).

Other optical imagery approaches, even if they cannot offer a full global monitoring due to particular observation (cloud cover and sun position), are unique in their resolving capability with, for example all coastal areas covered by Landsat and Sentinel 2A and 2B satellites. **Figure 5** shows an example of a Sentinel 2 image and the wave analysis from it compared to wave data from NDBC buoy 46086. The omnidirectional spectrum (panel c), shows overall good agreement with the measurements from the wave-buoy.

3. SCIENCE TOPICS: COMMUNITY NEEDS FOR INTEGRATED OBSERVATIONS OF SURFACE CURRENTS, WINDS, AND WAVES

3.1. Open Ocean Circulation and Budgets

3.1.1. Equatorial Dynamics

Climate variability in the tropical oceans is dominated by air-sea interactions associated with thermodynamic and dynamic feedback mechanisms. Surface wind is a crucial parameter for the turbulent heat flux, which has implications, for example, for establishing the meridional climate mode in the Atlantic. At the same time, surface winds dynamically drive tropical upwelling along the eastern boundary and at the equator. The zonal winds along the equator are an integral element of the Bjerknes feedback responsible for the development of the Pacific El Niño or the Atlantic Niño (Bjerknes, 1969). Besides the wind, ocean surface velocity is an essential parameter defining tropical ocean dynamics and air-sea interactions including processes, such as equatorial waves, tropical instabilities, as well as heat and freshwater advection and entrainment contributing to the mixed layer budgets (Foltz et al., 2018). Surface velocity divergence and associated upwelling is responsible for changes in the mixed-layer depth that is additionally forced by air-sea buoyancy fluxes or mixing and entrainment at the base of the mixed layer. The mixed-layer heat budget represents a central

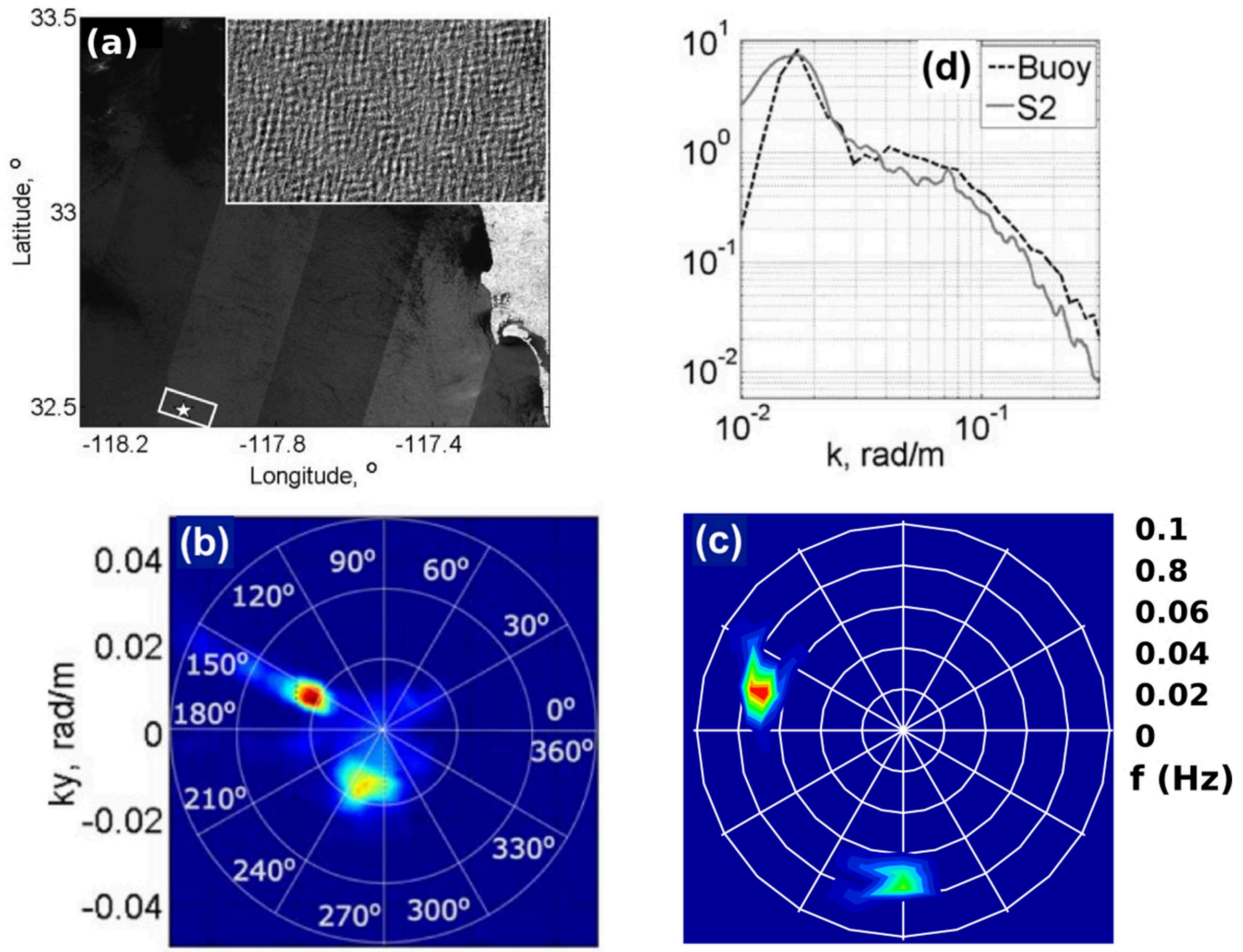

FIGURE 5 | (a) A Sentinel-2 image off the California coast taken on 29, April 2016. The inset delimits the region over which the spectral analysis (shown in the other panels) is performed and the star marks the location of the NDBC buoy 46086. **(b)** The two dimensional unambiguous image spectrum, over the area show in the inset on **(a)**, from Sentinel-2 using the time separation of different detector acquisitions. Blue colors indicate low wave energy density, whereas warm colors indicate high wave energy density **(c)**. The directional spectrum from the NDBC buoy 46086 estimated using the maximum entropy method of Lygre and Krogstad (1986). **(d)** The direction-integrated surface wave spectrum from the Sentinel-2 (solid) corresponds well to the buoy data (dashed) for wavelengths from 62 to 420 m, namely *k* between 0.015 and 0.1 rad/m or frequency from 0.06 to 0.15 Hz. This figure is adapted from Kudryavtsev et al. (2017).

element for understanding the mechanisms governing tropical SST variability and the causes of the still severe biases in tropical regions in climate models (Zuidema et al., 2016). Within the seasonal cycle, zonal advection is, besides diapycnal mixing, the main cooling agent in the central equatorial Atlantic, and a dominant term in the mixed-layer salinity budget (Foltz and McPhaden, 2008). Eddy advection mostly by tropical instability waves counteracts the cooling by diapycnal mixing in the eastern equatorial cold tongue region (Weisberg and Weingartner, 1988; Hummels et al., 2014).

Up to now, velocity data used to estimate tropical mixed-layer heat and freshwater budgets are based on spatially distributed surface drifters and surface displacements by Argo floats, as well as on velocity observations at moored buoys. Surface drift data allow climatological mean heat advection to be estimated and, in combination with total advection derived from temperature changes along Lagrangian surface drifter paths, eddy heat advection (Swenson and Hansen, 1999). However, mean seasonal budgets have substantial error estimates (Hummels et al., 2014), indicating the inadequacy of combined drifter and float data for addressing interannual variability or long-term changes of advective terms within the heat and freshwater budgets. Moreover, the mixed-layer depth in tropical upwelling regions is often <10 m. Under such conditions, surface drifters, equipped with drogues centered at 15 m depth, measure velocity in the shear zone below the mixed layer and thus do not represent mixed-layer advection. Argo floats drifting at the surface instead measure the velocity in the upper meter of the ocean, which becomes complicated for mixed-layer budget calculations due to the existence of diurnal shear (Smyth et al., 2013; Wenegrat and

McPhaden, 2015). Moored velocity observations performed at the tropical buoy array at a depth of 10 m deliver high-resolution time series. However, the spacing between the buoys (typically more than 10 degrees in longitude and a few degrees in latitude) do not resolve the near-equatorial current bands or the mesoscale variability including tropical instability waves. Surface currents from merged products, such as OSCAR, described in section 2.2.1, are often used in addition to directly-measured velocities from drifters, floats, and moorings. While OSCAR velocities are generally a well-proven data product, they largely fail to represent intraseasonal meridional velocity fluctuations near the equator and misrepresent seasonal and longer-term equatorial zonal velocity variability (Schlundt et al., 2014).

Continuous high-resolution measurements of absolute surface velocity would represent a significant step forward by improving mixed-layer heat and freshwater budgets and by refining our understanding of the general circulation of the tropical ocean. At the same time they would pave the way for new process studies, for example by enabling study of the role of tropical instability waves on the heat budget (Jochum et al., 2004) or the imprint of equatorial deep jets or high baroclinic mode waves on the sea surface and their impact on SST (Brandt et al., 2011), none of which are currently possible due to limited and sparse data coverage.

3.1.2. Atmospheric-Ocean Carbon Exchange and Transport

The oceans act as a sink of atmospheric carbon dioxide (CO_2), and they are the largest long-term natural sink of CO_2 (Sabine et al., 2004), annually absorbing more than 25% of anthropogenic emissions (Le Quéré et al., 2017). Quantifying this absorption is critical for quantifying global carbon budgets (e.g., as quantified by Le Quéré et al., 2017). Once dissolved in seawater, CO_2 is partitioned into different carbonate species, and these are transported throughout the ocean. This long-term absorption of carbon is slowly lowering the pH of the water, impacting the marine environment. Consequently the synoptic and long-term monitoring of the atmosphere-ocean exchange of carbon and the subsequent transport of carbon within the ocean interior and across continental shelves is highly relevant to society. We are currently able to observe the total atmosphere-ocean exchange of CO_2 (e.g., Watson et al., 2009; Woolf et al., 2016), and synoptic scale observations of this exchange require both satellite observations (e.g., sea state, temperature, wind) and *in situ* observations (e.g., gas concentrations). Existing synoptic scale observations of surface transport predominantly rely upon satellite altimetry or exploit spatially and temporally sparse *in situ* measurements (e.g., Painter et al., 2016).

However, atmosphere-ocean gas exchange is primarily driven by surface turbulence, such as wind-wave-current interactions, but most gas exchange relationships are parameterized solely in terms of wind speed (e.g., Wanninkhof, 2014). Similarly, the exchange of waters between the shelf seas and the open ocean (at both the surface and at depth) is highly dependent upon surface currents flowing onto the shelf, which include ageostrophic components not well-captured by altimetry.

A lack of suitable synoptic-scale measurements of surface currents, winds, waves, and their interactions hampers our understanding how these processes combine and control atmosphere-ocean exchange and across-shelf exchange. Doppler oceanography from space has the potential to address this gap in observations. For example, satellite sensors which are able to directly observe wind-wave-current interactions hold the potential to provide direct observations of energy dissipation and turbulence at the surface. This would enable the development and evaluation of new physically based atmosphere-ocean gas exchange parameterizations.

3.1.3. Inertial Currents

"Inertial currents" or "inertial oscillations" occur when the Coriolis force causes water that is moving only by virtue of its own inertia to rotate anticyclonically (clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere) at the local Coriolis (or "inertial") frequency. Whenever there is a short-lived wind event, such as a storm, the inevitable result is a mixed-layer inertial current, because the ocean freely resonates at the inertial frequency. In addition, the ocean can also be forced to resonate at the inertial frequency if the wind vector rotates at this frequency (e.g., D'Asaro, 1985).

Frequency spectra of oceanic velocity records almost always exhibit a prominent spectral peak near the local inertial frequency, and these near-inertial oscillations are typically the dominant velocity signal in the open ocean at periods less than a few days (e.g., Fu and Glazman, 1991). Inertial oscillations are an important source of vertical shear in the ocean and can thus drive vertical mixing (e.g., Alford, 2010). There are several unresolved research questions related to upper-ocean inertial currents, including ones related to the energy input from the wind to inertial motions, the interaction of inertial oscillations with mesoscale motions (Alford et al., 2016), and the amount of inertial energy that penetrates below the mixed layer via near-inertial waves (e.g., MacKinnon et al., 2013). Because near-inertial oscillations tend to be the largest contribution to velocity variability at periods less than a few days, they are also important for operational applications.

These high-frequency inertial currents pose a sampling challenge for the limited temporal sampling for the WaCM, SKIM, or SEASTAR missions (on the order of a day for WaCM), but there are three factors that should make this challenge more manageable. First, while the inertial oscillations are more prominent than other high-frequency motions, they still have less variance than lower frequency motions, such as mesoscale eddies, which limits the potential contamination of low frequencies. Second, it may be possible to remove inertial currents that are not well-resolved in time using simple dynamical models, which have shown skill in simulating mixed-layer inertial currents given estimates of the local wind stress (e.g., D'Asaro, 1985; Plueddemann and Farrar, 2006), and continuing improvements in ocean general circulation models and the forcing fields should allow even more realistic simulations (e.g., Simmons and Alford, 2012; MacKinnon et al., 2017). Finally, ongoing work from numerical simulations suggests that one could use physical properties of inertial oscillations to better separate low and high frequencies. Since inertial oscillations ring for several inertial periods, their amplitude and phase could be estimated even if they are not resolved in time, for instance, with daily observations of velocity.

3.1.4. Lagrangian Pathways of Plastic Debris and Other Floating Material

The issue of marine debris, most prominently plastic, has received significant attention in the last decade. There are at least a few trillion pieces of plastic afloat on the surface ocean, weighing at least 100,000 metric tons (Van Sebille et al., 2015). This plastic enters the ocean from coastlines and rivers (Jambeck et al., 2015; Lebreton et al., 2017) and is then transported by currents, waves, and winds. Due to biofouling, most of the plastic will beach or sink on time scales of weeks to years, but the fraction that stays afloat will eventually move into one of the infamous garbage patches in the centers of the subtropical gyres (e.g., Law et al., 2010, 2014; Law, 2017), where it can linger for many decades.

The transport and pathways that this floating material takes are very sensitive to the ocean currents, on scales from meters to kilometers (LaCasce, 2008; D'Asaro et al., 2018). Furthermore, it has recently been shown that Stokes drift can have a profound impact on the basin-scale pathways of floating material. Using a finding of invasive kelp on the shores of the Antarctic Peninsula, that was genetically identical to kelp found on the Kerguelen Islands, Fraser et al. (2018) were able to explain the southward transport of floating kelp against the dominant Ekman transport only when they included Stokes drift in their model simulation; without this Stokes drift, no Lagrangian particles were able to travel from Kerguelen to Antarctica.

It has long been known that surface drifting buoys travel differently when they are drogued vs. when they are undrogued (Lumpkin and Pazos, 2007). The tsunami following the Fukushima disaster also highlighted the importance of windage in cross-basin transport (and particularly speed) of debris. In order to be able to compute the dispersion of floating debris, biological material and human-made objects in search and rescue, it is critical to have as accurate flow, waves and winds fields as possible (Van Sebille et al., 2017). Ideally, these should come from novel remote sensing techniques capable of measuring surface winds, total surface currents, and waves globally.

3.2. Coastal, Shelf, and Marginal Ice Zone Processes

3.2.1. Continental Shelf Flows

At time scales longer than diurnal, currents on continental shelves and shelf slopes tend to flow nearly along-isobath (Lentz and Fewings, 2012) and often transport water for long distances along shelves. An example is the current system that transports water from east of Greenland, around the Labrador Sea to the Gulf of Maine and Middle Atlantic Bight, before turning offshore at Cape Hatteras (Chapman and Beardsley, 1989; Fratantoni and Pickart, 2007). The quasi-continuous shelf flow and shelfbreak jet system is an important conduit of cold low salinity water from high to mid latitudes in the western North Atlantic (Lentz, 2010) and transports anomalies in both heat and salt (Shearman and Lentz, 2010; Feng et al., 2016). Similar shelf current systems exist in other ocean basins. In the southwestern Atlantic, for example, there is a continuous along-shelf flow that transports high-nutrient waters from the Drake Passage to the Brazil/Malvinas Confluence (Matano et al., 2010). We do not have long-term observations or monitoring of the intraseasonal to interannual variations of these important continental shelf and shelf break current systems except in a few locations with moored current meter arrays (e.g., https://oceanobservatories.org/array/coastal-endurance/ and https://oceanobservatories.org/array/coastal-pioneer/). Satellite altimeters presently give limited information on flows on continental shelves, especially shoreward of the shelf break, except in regions with tide gauges (Feng et al., 2016; Risien and Strub, 2016). The along-shelf velocities along both eastern and western ocean boundaries are 10s of cm s^{-1} and could be monitored with Doppler surface current measurements. Simultaneous observations of winds would permit better understanding of the forcing of these shelf flows, which are driven by a combination of wind and along-shelf pressure and density gradients (Pringle, 2018). A better understanding of the dynamics of continental shelf, shelf break, and slope flows would lead to better capability for ocean monitoring and prediction, such as monitoring across-shelf exchange of carbon, heat, nutrients, and marine debris and improving seasonal forecasts of shelf water conditions in the downstream direction. Such capability would improve our understanding of the connections between shelf and deep ocean waters, allowing us to better anticipate the impacts of large spatial and temporal scale phenomena, such as our changing climate, on coastal regions.

Though continental shelf flows are constrained by the Earth's rotation to flow mostly along-isobath on long time scales, continental shelves do exchange water with the adjacent open ocean, with consequences for marine productivity (Brink, 2016b). Shelf eddies (Brink, 2016a, 2017; Brink and Seo, 2016), for example, play important roles in cross-shelf transport of heat, freshwater, and biogeochemical tracers. Deep-water mesoscale eddies and warm- and cold-core rings impacting the shelf slope can draw filaments of shelf water offshore or inject offshore water onto the shelf (Gawarkiewicz et al., 1990; Zhang and Gawarkiewicz, 2015; Cherian, 2016; Cherian and Brink, 2016, 2018). In other regions, such as the Brazil/Malvinas Confluence, exchange between the shelf and the deep ocean is not only controlled by eddies but also by narrow and well-defined coastal currents (Piola et al., 2005; Matano et al., 2010). The spatial scales of the shelf eddies and the filaments are 10–50 km, and the velocity scale is 10s of cm s^{-1}. Measurements of the velocity structure of these eddies, filaments, and narrow coastal currents, and simultaneously the wind fields that affect transport in the surface boundary layer, would enable better understanding of ocean productivity and shelf-ocean exchange of carbon, pollutants, and other substances.

Wind-driven cross-shelf transport is an important mechanism for nearshore-midshelf and shelf-ocean exchange. In broad, shallow shelf seas, cross-shelf transport of water can bring open ocean low nutrient surface waters onto the shelf, and help to force the offshore transport lower in the water column of carbon rich water from the shelf to the deep ocean, sometimes called the "Ekman drain" (Painter et al., 2016). In eastern boundary upwelling systems (Chavez and Messié, 2009) where the mean wind forcing is substantial, upwelling brings nutrient rich, but low pH, low oxygen water to the surface, which can be detrimental to marine ecosystems (Grantham et al., 2004; Chan et al., 2008; Connolly et al., 2010; Siedlecki et al., 2015; Adams et al., 2016). Weakening, or relaxation, of upwelling-favorable winds in these systems can enable transport of carbon off the shelf (Karp-Boss et al., 2004; Hales et al., 2006) and lead to coastally trapped warm oceanic poleward flows with cross-coast scales of 10s of km or less and velocities of 10s of cm s^{-1} (Washburn et al., 2011; Suanda et al., 2016). Coastal and shelf seas are considered important for the surface absorption of atmospheric CO_2, but the strength and state of this sink remain uncertain (Hales et al., 2005; Chen et al., 2013; Laruelle et al., 2014) and may diminish in the future due to changes in climate, environmental conditions and management (Regnier et al., 2013). On shallow inner shelves where the surface and bottom boundary layers overlap, the dynamics controlling the flow are different from on the middle and outer shelf (Fewings and Lentz, 2010; Lentz and Fewings, 2012). On broad shelves characteristic of passive continental margins, the inner shelf may extend 10s of km offshore, depending on the wind forcing and density stratification. In this region, cross-shelf winds and surface gravity waves can both drive cross-shelf flows, in contrast to the middle and outer shelf where the along-shelf wind is the primary driver for cross-shelf transport (Fewings et al., 2008; Lentz et al., 2008; Kirincich et al., 2009; Horwitz and Lentz, 2014, 2016). Due to the asymmetry in fetch for onshore and offshore winds in coastal areas, low-frequency flows associated with surface gravity waves, apparently due to Stokes-Coriolis forcing, can confound observations of wind-driven surface flows (Fewings et al., 2008; Kirincich et al., 2010; Ohlmann et al., 2012). Surface currents within ∼10 km of the coast can vary on alongshore scales <10 km and be poorly correlated with or even opposite in direction to currents farther offshore (Fewings et al., 2015). These alongshore flows are important for modifying local water temperatures on both weather-band and seasonal time scales (Austin, 1999; Fewings and Lentz, 2011; Connolly and Lentz, 2014). Simultaneous measurements of the surface currents, surface waves, and local wind stress along coastlines worldwide would enable monitoring of ongoing changes in ecologically and economically important boundary current systems (García-Reyes and Largier, 2010) and better process-based understanding, modeling, and prediction of cross-shore transport of nutrients and pollutants, transport of phytoplankton and larvae (Cowen and Sponaugle, 2009; Drake et al., 2013; Simons et al., 2013; Criales et al., 2015), and coastal fisheries productivity (Kaplan et al., 2016; Siedlecki et al., 2016).

River plume outflows and the resulting fresh coastal currents are heavily influenced by local wind forcing (Garcia Berdeal et al., 2002). During upwelling-favorable winds, the plume waters are transported offshore and the wind causes dilution of the plume by mixing with ambient ocean water (Fong and Geyer, 2001; Lentz, 2004; Hickey et al., 2005). Conversely, in light wind conditions or under downwelling-favorable winds, the plume becomes trapped against the coast and can propagate rapidly (>1 m s^{-1}) alongshore for 10s to hundreds of km, spreading nutrients, larvae, and pollutants (Münchow and Garvine, 1993; Rennie et al., 1999; Fong and Geyer, 2002; Lentz et al., 2003; Hickey et al., 2005; Lentz and Largier, 2006). Individual SAR images can show these plumes in great detail (Donato and Marmorino, 2002) but do not provide information about the time evolution of the plumes. In the Pacific Northwest in the U.S., the $100M shellfish industry (Dumbauld et al., 2011) is affected when Columbia River plume waters enter nearby estuaries, modifying the water chemistry in areas where oyster aquaculture takes place (Banas et al., 2004). In the southwestern Atlantic, the freshwater discharge from the Rio de la Plata extends hundred of kilometers, influencing the most densely populated regions of Argentina, Uruguay and Brazil and affecting some of the richest marine ecosystems of the South Atlantic (Piola et al., 2005). The strong fronts associated with river plumes affect the transport and fate of pollutants, including oil spills (Roth et al., 2017). The plume currents are 10s of cm s^{-1} to 1 m s^{-1}, strong enough to be detected by satellite Doppler scatterometer. Numerical models and observations suggest surface waves can also contribute to the mixing and dilution of the plume waters (Gerbi et al., 2013; Thomson et al., 2014). High-resolution satellite measurements of the velocity variations in these plumes together with the local wind and wave forcing would enable tests of new models for the evolution of the river plumes (Chen and Chen, 2017; Hetland, 2017) and the effects of the plumes on pollutant transport (Kuitenbrouwer et al., 2018). Fresh coastal currents in fjords and inland seas, such as Puget Sound or the inland sea in Chilean Patagonia, also transport harmful algal blooms that affect aquaculture operations. Better understanding and prediction of the behavior of river plumes and coastal currents from simultaneous satellite measurements of winds, surface currents, and surface waves would benefit management of shellfish aquaculture, oil spills, and harmful algal blooms.

3.2.2. Orographic Wind Intensification and Small-Scale Coastal Flows

Orographic wind intensification near coastal capes, reduced wind stress in the lee of capes, and wind jets through mountain gaps all generate ocean currents in response to the spatially varying wind field (Pringle and Dever, 2009; Perlin et al., 2011; Ràfols et al., 2017). Both along-shore variations in along-shore winds and smaller scale cross-shelf variations in winds affect the shelf flows and spatial structure of upwelling over the shelf. The wind and current features can have scales <25 km (Winant et al., 1988; Perlin et al., 2011; Rahn et al., 2013; Fewings et al., 2015). The long-term variability of these flows is not well-characterized by existing measurements, and knowledge of the spatial variability is limited to locations with aircraft studies and HF radar (Kim et al., 2011; Ràfols et al., 2017). In the lee of capes in eastern boundary upwelling systems, "upwelling shadows" create regions of low wind speeds and warm sea-surface temperature, accompanied by near coastal flows opposite to the direction of the prevailing regional wind (Graham and Largier, 1997; Roughan, 2005a,b; Piñones et al., 2007; Ryan et al., 2008, 2014; Woodson et al., 2009; Walter et al., 2016, 2018). When the regional wind weakens or "relaxes" periodically (Fewings et al., 2016; Fewings, 2017), the local diurnal wind patterns and ocean stratification change (Aristizábal et al., 2017). Therefore, the regional wind relaxations not only cause regional sea-surface temperature variability offshore (Flynn et al., 2017) but also lead to changes in the coastal cross-shore flows on diurnal and semidiurnal time scales, affecting the internal temperature variability (Aristizábal et al., 2016), which is associated with nutrient supply to kelp forests in marine protected areas (McPhee-Shaw et al., 2007; Fram et al., 2008). More comprehensive measurements of the wind and current variability associated with coastal capes would enable better understanding and process-based modeling of upwelling of nutrients and retention of larvae and phytoplankton, including harmful algal blooms, in the lee of capes, and nutrient supply to marine protected areas, all processes that affect fisheries productivity.

Surface wave variability in coastal areas on scales of 25 km and smaller can be created locally by spatial variations in winds, currents, or bottom topography. High winds in hydraulic expansion fans near capes and coastline bends (Winant et al., 1988; Rogerson, 1999; Edwards et al., 2002; Monteiro et al., 2016) are the source of much of the wave energy in those regions (Villas Bôas et al., 2017). When these high winds weaken during wind relaxation events, coastally-trapped wind reversals can result (Nuss et al., 2000). The trapped reversal events are difficult to capture in existing numerical weather prediction (NWP) models due to the small cross-coast scale of the wind reversals (∼10–20 km), but the reversals are associated with thickening of the marine boundary layer and tend to cause fog formation (Dorman et al., 2017) and reduced wave heights in regions that frequently experience large wind waves (Villas Bôas et al., 2017). Better observations of these topographically controlled wind intensification, relaxation, and reversal events and the associated wave heights from high-resolution satellite data would enable improvements in modeling and forecasting marine navigational hazards. Numerical models of surface waves show substantial along-coast variability in wave heights near shore due to refraction over canyons and other bathymetric features on continental shelves (García-Medina et al., 2013). Temporal and spatial variability in wave heights also occurs due to coastal boundary jets formed when mountains block passing fronts (Ellenson and Özkan-Haller, 2018). Fully coupled models for wave and current prediction are underway to aid safety and planning for marine shipping and navigation, especially near river mouths (Akan et al., 2017); simultaneous satellite measurements of winds, waves, and surface currents would enable testing and improving these models.

3.2.3. Island Wakes and Flows Around Submarine Banks

Island wakes in the ocean are important sources of upwelling of nutrients to support biological productivity. The oceanic wakes are driven by both wind variability due to the small-scale wind divergence and curl generated by the island (Caldeira et al., 2005) and by topographic effects in the ocean (Xie et al., 2001). The currents in these wakes have spatial scales of km to 10s of km and velocities of 0.2–1.5 m s^{-1} (Teinturier et al., 2010). Though HF radar surface current measurements have been made around some islands, such as Hawaii and Puerto Rico (https://hfradar.ioos.us/), for many geographically isolated islands the shoreline geometry does not permit overlapping coverage from two or more radars, which is needed to derive both components of the horizontal current. In addition, little information is available about the wind field within ∼25 km of many islands due to the small-scale variations in the wind, the difficulty of maintaining *in-situ* buoy measurements, and the land mask of existing satellite measurements. Simultaneous, high-resolution measurements of winds and currents from satellites would enable better understanding and modeling of the dynamics that control these upwelling island wakes, including their dependence on ocean stratification, and whether the fisheries productivity near these islands is vulnerable to future changes in ocean stratification. Such understanding could be particularly variable in the assessment of dynamical processes that supply nutrients in the Southern Ocean, where areas near islands such as South Georgia and Kergulean are the main regions of carbon drawdown (Schlitzer, 2002).

Submarine banks are often locations of valuable fisheries, such as at Georges Bank off the northeastern U.S. (Miller et al., 1998). The partial barrier to flow on and off a bank created by the tidally-rectified flow and tidal mixing front around the bank (Houghton and Ho, 2001) provides an important retention mechanism for the plankton that support high fish production (Lough and Manning, 2001; Wishner et al., 2006). The spatial scales of the currents associated with the front are ∼10–25 km (Loder and Wright, 1985; Loder et al., 1992). However, the water velocity variability on subseasonal time scales, and the interannual variability, are not well-known. Numerical modeling suggests wind forcing is also important for providing a mechanism for nutrients to be supplied to the bank across the tidal mixing front (Chen, 2003). On longer time scales, off the northwest U.S., pressure gradients associated with Heceta Bank off Oregon strongly influence the along-shore currents and local upwelling and retention patterns (Kirincich and Barth, 2009). Simultaneous measurements of winds and currents over submarine banks would enable better understanding of the physical forcing of these economically valuable ecosystems by enabling tests of dynamical models of such flows (Brink and Cherian, 2013; Dong et al., 2015) and supporting fisheries management.

3.2.4. Diurnal Variability of Surface Winds

The Earth's 24-h rotation period drives diurnal variability in atmospheric and upper ocean temperatures, winds, air-sea fluxes, and upper ocean mixing (e.g., Gille et al., 2003, 2005; Dai and Trenberth, 2004; Gentemann et al., 2009). Diurnal wind variability is most prominent along coastlines, where the land-sea breeze circulation is driven by differential daytime warming of the land and ocean (Simpson, 1994), but the signatures of diurnal winds are detectable throughout the tropics (Dai and Deser, 1999). The diurnal cycle in the upper ocean is mainly forced by solar heating, yet diurnal and higher-frequency winds play an important role in regulating vertical mixing (e.g., Giglio et al., 2017), and air-sea fluxes of heat and gases. High-frequency wind variability also impacts cross-shore exchanges (e.g., Hendrickson and MacMahan, 2009) and larvae transport (e.g., Fujimura et al., 2014).

If only one component of the Earth system experienced diurnal variability (surface air-temperature, for example), then the diurnal oscillation might be expected to cancel itself out, so that only the daily-average value would ultimately influence long-term processes. In reality, since multiple variables undergo diurnal cycles, they interact non-linearly and thus can produce a net rectified effect, working together to determine upper-ocean mixing, planetary boundary layer structure, sea surface temperature and surface air temperature (e.g., Lee and Liu, 2005).

New high-resolution wind observations, coordinated with currents, waves, and other variables, have the potential to provide the information needed to evaluate diurnal interactions of winds, temperature, and other processes. Most Earth-observing satellites have been launched on sun synchronous orbits, with measurements at two fixed times each day (e.g., 6 am and 6 pm local time). Sun-synchronous measurements are effectively at the Nyquist frequency of the diurnal cycle, providing insufficient information to resolve the details of the diurnal cycle. A greater understanding of coupled diurnal processes could be gained through a multi-satellite approach or by using a carefully selected non-sun-synchronous orbit.

3.2.5. Processes in Marginal Ice Zones and Polar Regions

In ice-covered regions the interface between atmosphere and ocean differs from its open ocean counterpart in many ways. The surface topography appears as frozen on time and length scales spanned normally by the surface wave spectra. Furthermore, the ice cover acts as an additional insulating layer both thermodynamically, due to the low conductivity of ice and snow, and mechanically, due to the rigidity of ice floes. The seasonal evolution of the sea ice drives a buoyancy forcing at the ocean surface via modulations of energy (wind forcing and heat fluxes) and salinity (brine rejection and freezing). In addition, the complex surface topography and two-phase nature of the sea ice, with alternating open ocean (leads in the pack ice or of open ocean in the MIZ) and ice features (floes), modifies turbulent fluxes of momentum, heat, freshwater, humidity, gas, and other tracers.

Sea ice in the Arctic is predicted to transition from a multi-year consolidated to a first-year seasonal fragmented ice (Aksenov et al., 2017) akin to the MIZ defined by low concentration conditions in the 15–80% range (Strong and Rigor, 2013) that are currently observed on a narrow band on the Arctic sea ice edges and more commonly throughout most of the Antarctic. This rapid transition is accompanied by a general decline in sea ice extent, concentration, thickness, age, and roughness of the ice cover (Stroeve and Notz, 2018) as well as a mechanical weakening and acceleration of the surface ice drift (Rampal et al., 2011). The increase in open water and related changes will offer new challenges and opportunities for observing and interpreting winds, waves, and currents, and their interactions. We summarize these issues below within the context of this paper.

In the MIZ, Heorton et al. (2014) found that the sharp change in surface roughness from the open ocean to the pack ice results in the formation of jets parallel to the sea ice edge over a band of ∼100 km in the atmosphere and ∼10 km in the ocean that modify accordingly the sea ice motion. Also in the MIZ, (Horvat et al., 2016) described in a model the interaction between floe size distribution, ocean eddies and sea ice at the origin of ocean-mixed-layer instabilities and energetic eddies at the sea ice edge that have been observed in SAR imagery (Ardhuin et al., 2017b). The MIZ can also be defined as the region over which the effects of the waves from the open ocean persist over the ice pack (Dumont et al., 2011) and to date the wave ice interactions are a key missing ingredient of sea ice-ocean coupled models (Squire, 2018). The mechanisms by which waves are dissipated in this transition region have been recently reviewed in (Boutin et al., 2018) and were shown to contribute significantly to the turbulent momentum fluxes between atmosphere and ocean (Stopa et al., 2018).

The state of the sea ice is controlled by an interplay of dynamics and thermodynamics on all spatiotemporal scales represented by a myriad of processes, such as ice growth and melt, mechanical strength of the ice, ridging, sea ice wave interactions, fast ice or leads formation (Notz and Marotzke, 2012). An observational gap remains at short time and length scales to resolve those faster processes. Marcq and Weiss (2012) found that while leads constitute <5% of the surface of the ice-covered sea they contribute to almost half of the turbulent losses. Frazil ice formation in leads and polynyas in winter (Heorton et al., 2014) and lateral melt and fragmentation of ice floes in summer (Tsamados et al., 2015), are modulated by high-frequency winds, waves and sea ice motion. Tides modify the fracture patterns over sea ice (Hutchings et al., 2005) and via a complex interplay with the sea ice and sea-floor bathymetry (i.e., at continental shelves slopes) can significantly enhance vertical turbulent fluxes (Rippeth et al., 2015). Sea ice has also been shown to act as an important controlling factor for ocean-ice shelves and marine-terminating glaciers interactions (Carr et al., 2014) via its mechanical buttressing effect but also in modulating the exchanges of heat and the degree of upwelling and impacting the amount of warm waters that can reach the continental shelves and melt ice shelves from below (Cowton et al., 2018).

The interaction between winds, ice drift, and surface ocean currents is also important in the pack ice. Over synoptic and slower time scales, the wind and ocean forcings, together with the internal forces in the sea ice (Steele et al., 1997; Feltham, 2008) control the sea ice motion and ultimately the total and regional ice volume contained in the polar oceans via redistribution of ice and export mostly out of the Fram Strait in the Arctic (Hibler et al., 2006; Ricker et al., 2018) or via Ekman transport to the warmer Southern latitudes in the Antarctic (Holland and Kwok, 2012). With the advent of polar oceanography from altimeters in ice-covered regions (Peacock and Laxon, 2004; Kwok and Morison, 2011), important new questions can now be addressed regarding the freshwater fluxes (Armitage et al., 2016), surface currents and Eddy kinetic energy (Armitage et al., 2017), as well as the spinning up or down of polar gyres (Giles et al., 2012; Dotto et al., 2018). To improve further upon the resolution probed by conventional altimetry requires the joint measurements of surface winds, ice drift and ocean currents at sub-synoptic and Eddy resolving length scales that SKIM, WaCM, and SEASTAR can achieve.

3.3. Wave-Current-Wind Interactions

3.3.1. Langmuir Turbulence

Langmuir turbulence, a physical process resulting from the interactions between the ocean surface waves and the wind-driven upper ocean sheared currents, transferring energy from the wave field to turbulence by the straining of vortices caused by the Stokes drift (Teixeira and Belcher, 2002; Ardhuin and Jenkins, 2006; Suzuki and Fox-Kemper, 2016). Langmuir turbulence is one of the most prominent wave-dependent processes that requires parameterizations in a global climate model (Belcher et al., 2012; Cavaleri et al., 2012; D'Asaro, 2014). Enhanced vertical turbulent mixing in the wavy ocean surface boundary layer (OSBL) as compared to a wall boundary layer are commonly seen in both the observations (e.g., D'Asaro, 2001, 2014; Kukulka et al., 2009) and Large Eddy Simulations (LES, e.g., McWilliams et al., 1997; Harcourt and D'Asaro, 2008; Grant and Belcher, 2009). Some of the ideas to parameterize the effects of Langmuir turbulence on vertical mixing include enhanced vertical eddy diffusivity and viscosity in the OSBL (McWilliams and Sullivan, 2000), enhanced entrainment at the base of the OSBL (e.g., McWilliams et al., 2014) and a down-Stokes drift-gradient momentum flux (Harcourt, 2013, 2015).

Parameterizing some of the effects of Langmuir turbulence in a global climate model has shown promising results, improving the simulated mixed layer depth and subsurface temperature in the extratropical regions, especially in the Southern Ocean (e.g., Li et al., 2016; Li and Fox-Kemper, 2017), although not all Langmuir turbulence parameterizations lead to climate model improvements (Fan and Griffies, 2014). Yet challenges remain in Langmuir turbulence parameterizations for global climate models. For example, due to the limited direct observations, the developments of Langmuir turbulence parameterizations have heavily relied upon LESs, which usually represent a quasi-equilibrium state and only focus on limited regimes in parameter space. The effects of Langmuir turbulence under transitioning conditions over a wide range of scenarios remain unexplored. In addition, the extent of the agreement between proposed Langmuir turbulence parameterizations remains unclear. Global-scale high-resolution measurements of ocean currents, waves, and winds will be invaluable for constraining the parameter space to be explored and for validating the parameterization schemes of Langmuir turbulence. Another challenge is the high computational cost of running a full wave model along with a climate model in order to provide the necessary wave information for Langmuir turbulence parameterizations. A wave climatology dataset has been shown to be useful for parameterizing the Langmuir turbulence-enhanced vertical mixing (Li and Fox-Kemper, 2017). Datasets from global-scale high-resolution wave measurements will be highly valuable for this purpose and potentially helpful for parameterizing other effects of Langmuir turbulence without a full-wave model.

Additionally, there are other known impacts of waves on upper-ocean turbulence and macroturbulence, such as wave breaking and bubble injection (Liang et al., 2013; Deike et al., 2016), and wave-driven submesoscale frontogenesis (McWilliams and Fox-Kemper, 2013; Suzuki et al., 2016). There are alternative theories and experiments of spontaneous turbulence driven by non-breaking waves and in the absence of prior turbulence (Babanin, 2006) that differ conceptually from Langmuir turbulence, but it is unclear to what extent these theories represent distinct phenomena as opposed to being alternative explanations of the same effects, because some theoretical framings include both aspects. Detailed laboratory experiments and high-resolution measurements of co-located currents, waves, and winds would be an ideal resource for evaluating these new and alternative theories and their impacts on global-scale questions, such as air-sea exchange and interactions and their impact on climate change.

3.3.2. Ocean Fronts

Observations, models, and theory indicate that in all regions and seasons, the ocean surface is filled with permanent, recurring, and transient fronts: strong horizontal gradients in buoyancy on an O(100 m–10 km) scale with magnitudes of 10^{-5}–10^{-8} s^{-2} (Small et al., 2008; McWilliams, 2017). Frontal regions have strong and atypical air-sea interactions (e.g., D'Asaro, 2001). Coupled models (Small et al., 2008) and observations (Frenger et al., 2013; Villas Bôas et al., 2015) indicate that SST contrasts at the front can localize responses in the atmospheric boundary layer above, which affects winds, clouds, uplift, turbulence, precipitation, turbulent heat fluxes, and wind shear profiles. This coupling is qualitatively different from coupling that occurs at larger scales, as oceanic variability tends to drive atmospheric variability, rather than vice versa. In addition, oceanic fronts have a different response to forcing than regions without fronts. In non-frontal regions, winds and cooling tend to deepen the boundary layer, while warming tends to shoal it. In frontal regions, observations and theory indicate that winds and cooling interact with the fronts–in particular, downfront winds tend to enhance fronts and trigger frontal instabilities (symmetric and baroclinic) and turbulence, while upfront winds tend to shoal the boundary layer (Thomas and Lee, 2005; D'Asaro et al., 2011; Thomas et al., 2013, 2016). Fronts refract and scatter waves and can lead to large gradients in surface roughness and wave forcing (Ardhuin et al., 2017a; Romero et al., 2017).

The origin of fronts is sometimes from localized atmospheric mixing (e.g., Price, 1981; D'Asaro et al., 2007; Mrvaljevic et al., 2013), sometimes from topographic features (e.g., Srinivasan et al., 2017) and river mouths (Luo et al., 2016), and sometimes through the straining by mesoscale features (Shakespeare and Taylor, 2013). Fronts and filaments can be enhanced by wave-induced vertical velocities by a mechanism similar to that driving Langmuir turbulence (McWilliams and Fox-Kemper, 2013; Suzuki et al., 2016) and through boundary layer mixing (Gula et al., 2014; McWilliams, 2017). The arrest and frontolysis that controls the width, strength, and lifetime of these features is an area of active research (Sullivan and McWilliams, 2018; Tozuka et al., 2018) and plays an important role in parameterizations that depend on frontal width (e.g., Fox-Kemper et al., 2011). The instabilities that form at fronts extend into the features that populate the macroturbulence of the submesoscale (Haine and Marshall, 1998; Haney et al., 2015) and form the basis of most submesoscale parameterizations (e.g., Fox-Kemper et al., 2011; Bachman et al., 2017). Significant surface convergence frequently occurs along the nose of the front, which is important for transport of buoyant debris and oil (D'Asaro et al., 2018) as well as for the strengthening of the front (Suzuki et al., 2016; McWilliams, 2017). Frontal strength–and related submesoscale variability–have strong seasonality because of the connections between fronts and air-sea interaction (Mensa et al., 2013; Qiu et al., 2014; Brannigan et al., 2015; Callies et al., 2015) and seasonality of boundary forcing, such as rivers (Luo et al., 2016).

What is presently not well-constrained observationally are the typical interactions at fronts between the fronts, winds, waves, and small-scale features. While there are many studies using *in situ* instruments to study these interactions (e.g., D'Asaro et al., 2007, 2011; Mrvaljevic et al., 2013; Thomas et al., 2013, 2016; Callies et al., 2015), and a few point source seasonal studies (e.g., Thompson et al., 2016), a global-scale survey of simultaneous fronts, winds, and waves does not exist. Without such a survey, many of the inferences from models and theory remain largely speculative. Note that the interactions between mesoscale strain, fronts, and turbulence induced by winds spans roughly five orders of magnitude in horizontal scales from 100 km to 1 m (**Figure 2**), which is orders of magnitude larger than the largest simulations presently possible. A global simulation resolving these processes remains over a century away (Fox-Kemper et al., 2014).

3.3.3. Surface Wave Response to Currents and Winds

Ocean waves respond differently to winds and currents, as illustrated in **Figure 6**. Away from coasts and sea ice, and at scales larger than 100 km, fields of wave heights are similar to low-pass filtered winds with a wavenumber spectrum of H_s that is steeper than the wind kinetic energy spectrum. At smaller scales, the variability of H_s is expected to be mostly due to refraction over current gradients (Lavrenov, 2013; Ardhuin et al., 2017a), and the wavenumber spectrum of H_s generally follows the shape of the current kinetic energy spectrum. Hence, sharp current fronts result in sharp wave heights and might enhance wave breaking (Phillips, 1984; Romero et al., 2017). When the average wave height is around 4 m, standard products from altimetry typically give three regimes as illustrated in **Figure 6C**: slopes on the order of k^{-1} for wavelengths longer than 100 km, probably associated with scales in the wind field; a k^{-3} slope for scales between 50 and 100 km, which follows the shape and level of the current kinetic energy spectrum; and a much flatter region at scales below a threshold on the order of 50 km, which we interpret as nearly white tracker noise. The effective resolution is even coarser for lower sea states, so that the nominal resolution of 25 km is generally not achieved, even in the along-track dimension of satellite data. This along-track resolution can be strongly improved with re-tracking (Ardhuin et al., 2017a) or filtering (Quilfen et al., 2018), and Delay-Doppler altimetry can produce less noisy estimates of H_s.

Even perfect satellite measurements of the wave field would not, at least in the near future, provide the 3-h revisit time required to resolve the temporal variability associated with storms and tidal cycles, which is now only available at discrete point locations with moored buoys. Hence, any progress toward faster revisit times, possibly by measuring across a wide swath and not just along a track, could take us closer to resolving the variability of sea states. Given accurate forcing fields, including surface vector winds, surface currents, and sea ice properties, sea states can be predicted fairly accurately once the wave generation and dissipation processes are well-documented and parameterized (e.g., Ardhuin et al., 2010). Observing the spatial patterns of wave heights and other sea state parameters is key to arriving at this understanding and improving the parameterization of source terms in wave models.

Indeed, significant wave height is only one parameter, and a full description of the sea state requires a two-dimensional (2D) spectrum for which few measurements are available. The 2D wave spectrum can be integrated to yield moments, such as the mean square slope and surface Stokes drift that are expected to impact wind stress and surface drift velocities, and different mean periods and directions that are needed to know the wave-induced energy flux, forces on structures or wave-induced coastal sea level variations.

3.3.4. Sea State Dependent Air-Sea Fluxes

Ocean waves define the random moving multi-scale interface between the ocean and the atmosphere, key subsystems governing the dynamics of climate. A precise description of the physical processes, forcings, interactions, and feedbacks occurring at this interface is essential for determining air-sea fluxes of momentum, sensible and latent heat, CO_2 and other trace gases, in addition to aerosols, which all together govern the coupling between the two subsystems. While there is an agreement among the oceanographic community that wave motions and dissipative breaking processes are intimately involved in all these fluxes (Cavaleri et al., 2012), surface wave physics has yet to be consistently represented in most air-sea interaction parameterizations.

Beyond atmospheric stability, measurements systematically indicate that surface wind stress can be significantly impacted by the sea state directionality, degree of development, interaction with upper ocean currents (e.g., Vandemark et al., 1997; Grachev et al., 2003; Hristov et al., 2003; Edson et al., 2013), and also by unsteady winds and the presence of swell (e.g., Hwang et al., 2011). Without considering all the aforementioned sources of inhomogeneous conditions, wind stress is already reported to be significantly enhanced with respect to a flat surface for winds up to 25 m s^{-1}. This has been well-captured by conceptual models (e.g., Janssen, 2004, and references therein). Several studies demonstrate that incorporating wave-dependent surface flux parameterizations leads to significant effects in the atmospheric state (e.g., Cavaleri et al., 2012; Shimura et al., 2017; Pineau-Guillou et al., 2018). Studies of the impact of small-scale breaking distribution and modulation have shown wave

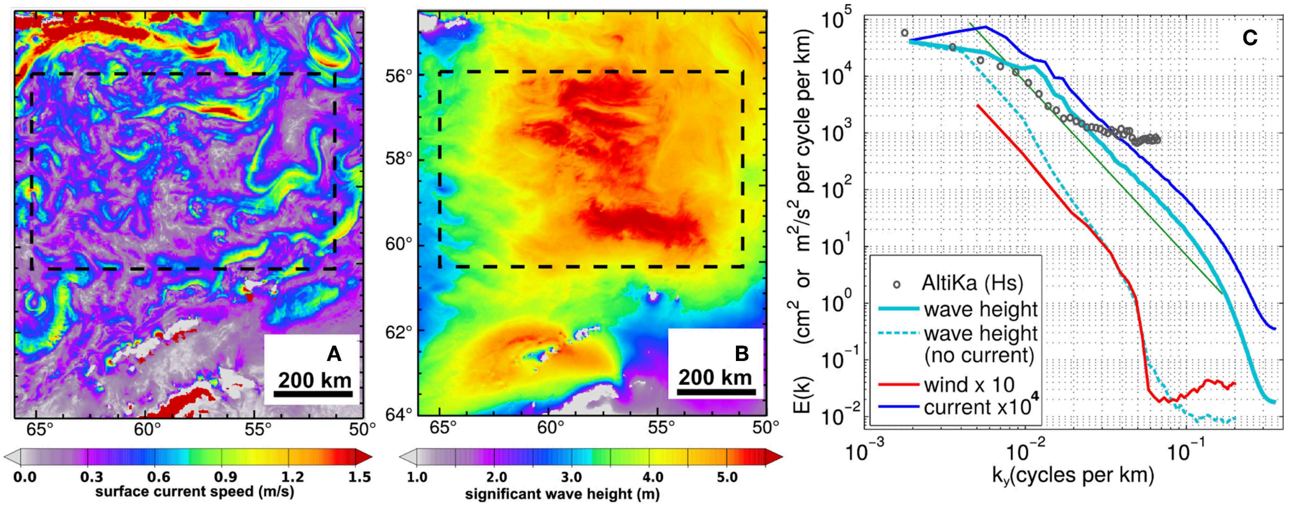

FIGURE 6 | (A,B) Show snapshots of modeled surface currents and waves in Drake Passage, respectively. **(C)** Shows corresponding spectra of modeled winds (red), currents (dark blue), and significant wave heights (light blue), as well as the spectrum of significant wave height observed from the AltiKa altimeter (circles). This figure is adapted from Ardhuin et al. (2017a). The green solid thin line has a k^{-3} slope.

breaking to be significant for momentum fluxes (e.g., Melville and Rapp, 1985; Kudryavtsev et al., 2014a; Kudryavtsev and Chapron, 2016). However, relating the variations of the sea surface drag coefficient to the degree of development of the sea state, significant wave steepness, phase velocity of dominant waves or wave age (e.g., Kitaigorodsky, 1970; Donelan et al., 1993) is still an open question.

In particular, measurements of surface stress are too scarce and often exhibit significant, and sometimes unexpected, scatter around the predicted equilibrium value for a given wind, which suggests that this variability could be due to a sensitivity to external parameters (Garratt, 1977; Edson et al., 2013). Under low wind conditions, the presence of swell is considered a major source of variability. For example, Soloviev and Kudryavtsev (2010) reported swell-induced wind-flow undulations, exponentially attenuated with heights up to half the peak wavelength. These results are in line with theoretical predictions (Makin, 2008; Kudryavtsev et al., 2014a). However, more accurate measurements of the complete wind-wave-current system are still needed to help understand the complex interplay between processes controlling air-sea interactions, possibly including physical-biological effects near upper-ocean fronts, such as biological surfactants and sea surface temperature influencing short-scale wave growth. Examples of recent experiments include ship observations in the frontally active Brazil-Malvinas confluence region (Hackerott et al., 2018), or airborne observations covering varying fetch and current conditions (Romero and Melville, 2010; Romero et al., 2017). These measurements are needed to proceed further in an improved description of the statistical properties of the turbulence and impacts on the profile of the atmospheric flow.

The observational challenge to be faced is first to improve the variety and the precision of the wind-wave-current state variables (e.g., better estimate atmospheric turbulence statistics, which requires an improvement in temporal sampling). Moreover, there is a need to design a coordinated array of surveys (e.g., a swarm of drones) to optimally document the variety of physical conditions in the wind-wave-current system and to explore how its heterogeneity can affect the resulting large-scale wind stress and surface flow.

3.3.5. Wind Modulation by Surface Currents

Winds drive ocean currents, but the ocean can also couple to the atmosphere through a surface current feedback (Dewar and Flierl, 1987; Pacanowski, 1987) or a thermal feedback (Chelton et al., 2004; Small et al., 2008; Chelton and Xie, 2010). The current feedback is due to momentum transfer between the ocean and atmosphere which occurs in the moving frame provided by the moving ocean, so that the surface stress, $\boldsymbol{\tau}$, is given by

$$\boldsymbol{\tau} = \rho C_D \left|\mathbf{U_a} - \mathbf{U_o}\right| (\mathbf{U_a} - \mathbf{U_o}) \tag{1}$$

where ρ is the air density, C_D is the drag coefficient, $\mathbf{U_a}$ is the air velocity, and $\mathbf{U_o}$ is the ocean velocity. The signature of surface currents on stress was first shown at large scales by Kelly et al. (2001, 2005), who showed that scatterometer neutral winds, which are proportional to $\boldsymbol{\tau}$, were modulated by equatorial currents at the TAO buoy array, and by Cornillon and Park (2001), who showed the same effect over mesoscale eddies. It was soon realized (Hughes and Wilson, 2008; Scott and Xu, 2009) that the net effect of the stress modulation resulted in energy flowing from the ocean mesoscale circulation into the atmosphere, damping the eddy kinetic energy (EKE). A detailed study of the interplay between surface currents and wind induced vertical pumping for mesoscale eddies was conducted by Chelton et al. (2011) and by Gaube et al. (2015), who observed patterns of upwelling for cyclonic and anticyclonic eddies, and estimated the eddy decay resulting from Ekman pumping and associated energy release into the atmosphere. Subsequently, in a study using coupled models in the California Current System (CCS), (Renault et al., 2016c) showed that the wind-stress curl could be approximately related to the surface current relative vorticity via a linear relationship

$$\hat{\mathbf{k}} \cdot (\nabla \times \boldsymbol{\tau}) \approx s_w(U_a)\zeta, \qquad (2)$$

where ζ is the current relative vorticity, and $s_w(U_a)$ is a (negative) coupling coefficient that depends on the wind speed. This relationship was also characterized for large mesoscales using coupled models for the Gulf Stream region (Renault et al., 2016b), the Agulhas Retroreflection region (Renault et al., 2017b), and globally, using satellite data (Renault et al., 2017a). This coupling is expected to depend on the scales of averaging, and a first look at the changes was obtained using a coupled model study for submesoscales in the CCS (Renault et al., 2018). The validity and scale dependence of this relationship is and important and open question. Recent airborne results using a Doppler scatterometer (Rodriguez and Wineteer, 2018; Rodriguez et al., 2018) document the validity of the relationship at very high (km-scale) resolution, as shown in **Figure 7**. Understanding the validity of this relationship globally at high resolution is an important goal for future winds and currents ocean observations. Among important applications of improved understanding of this coupling is the impact of wind and current interactions for ocean productivity (Gaube et al., 2014; Renault et al., 2016a).

The other source of coupling between currents and winds is due to the influence of heat carried by surface currents to alter the marine boundary layer, leading to increases (decreases) of wind speed as winds travel from cold to hot (hot to cold) ocean regions. A linear relationship between sea-surface temperature (SST) gradients and wind speed, wind stress, and wind-stress curl has been documented by multiple studies (O'Neill et al., 2003, 2005, 2010, 2012; Chelton et al., 2004, 2007; Liu et al., 2007; Small et al., 2008; Chelton and Xie, 2010; O'Neill, 2012). Coupling also has an impact of Ekman upwelling for ocean eddies, although the effect is much smaller than the coupling caused by current modulation (Gaube et al., 2015). However, this coupling has been shown to have an impact on winds, clouds, rain, and turbulent heat fluxes for the lower atmosphere (Frenger et al., 2013; Villas Bôas et al., 2015), with the potential to reach higher in the atmosphere for western boundary currents (Minobe et al., 2008, 2010). Since the magnitude of the coupling depends on the SST gradient, it is expected that the coupling will appear more pronounced when observed at higher resolutions for sharper SST fronts than have been observed to date, and this is also an important issue to be settled by future ocean observations.

3.4. Modeling and Data Assimilation

Fundamentally, data assimilation seeks to extract and combine the maximum amount of information contained in observations and numerical models to obtain a more complete and synthetic view of the system considered. Stammer et al. (2016) note that the generic term "data assimilation" encompasses two distinct approaches. Numerical weather prediction (NWP), or ocean prediction, is focused on near-real-time (NRT) prediction and it is done operationally, by sequentially updating the model state to make the best possible forecasts. Error in the model physics and dynamics and sparse data are major obstacles to skillful analyses and forecasts. The second approach is state (and parameter) estimation, which is usually focused on hindcasts, also called reanalysis, which test models by requiring them to match the time evolution seen in the observations. The purpose of state estimation is to reconstruct the past, evaluate prediction skill as well as identify model errors and reduce them.

Model errors are often largest in boundary regions where important physics at small scales are unresolved and must be parameterized. The most important boundary layer is the interface between the ocean and atmosphere. Reducing model error in this boundary layer requires representing the coupling physics and dynamics as accurately as possible, but these physics must be learned from theory, modeling, and observations together. Overlapping observations of wind, current, and surface waves will enable process studies to develop and refine our understanding of the surface layers, using models in the data analysis to enforce known physics. Identifying model errors is a challenging problem and requires comprehensive observations that can both supply enough information to specify the model state and check its evolution over time. The first step is to adjust the physics to maximize the consistency of the model with the observations over a time range that is comparable or longer than the timescale of the dynamics under investigation, but models can fit the observations for the wrong reasons if the dataset is insufficient to determine all the model parameters within errors that are small enough. A second step of cross-validation against observations not used in the assimilation (called "independent" or "withheld") may guard against this (Cornuelle et al., 2000; Verdy and Mazloff, 2017), although there is some debate on the functionality of this method for heavily under-sampled systems.

Many of the open questions for the physics of the boundary layer come from the turbulent flows above and below the air-sea interface, where waves are a key component. Knowledge of the sea state should improve model estimates of momentum, heat, mass, and gas fluxes (Cavaleri et al., 2012; Shimura et al., 2017). Moreover, propagation of observation information between the atmosphere and ocean model components will be improved by the inclusion of a wave model component. Weather forecasts beyond a week or two are increasingly thought to depend on accurate air-sea fluxes, so accurate modeling of the air-sea boundary layers should enhance sub-seasonal to seasonal predictions (Belcher et al., 2015). Including a wave model component to a coupled ocean-atmosphere model could reduce both data and model error. Several observational platforms (e.g., altimeters) cannot completely remove ocean wave signals and thus having a wave component in the assimilation system may help to unbias the observations (e.g., Peral et al., 2015). Ocean-atmosphere assimilation systems may also benefit from fully incorporating wave models due to the coupling of these components. There will be instances where observations of waves will constrain estimates of the atmosphere and ocean states, although they cannot replace direct measurements of winds and currents.

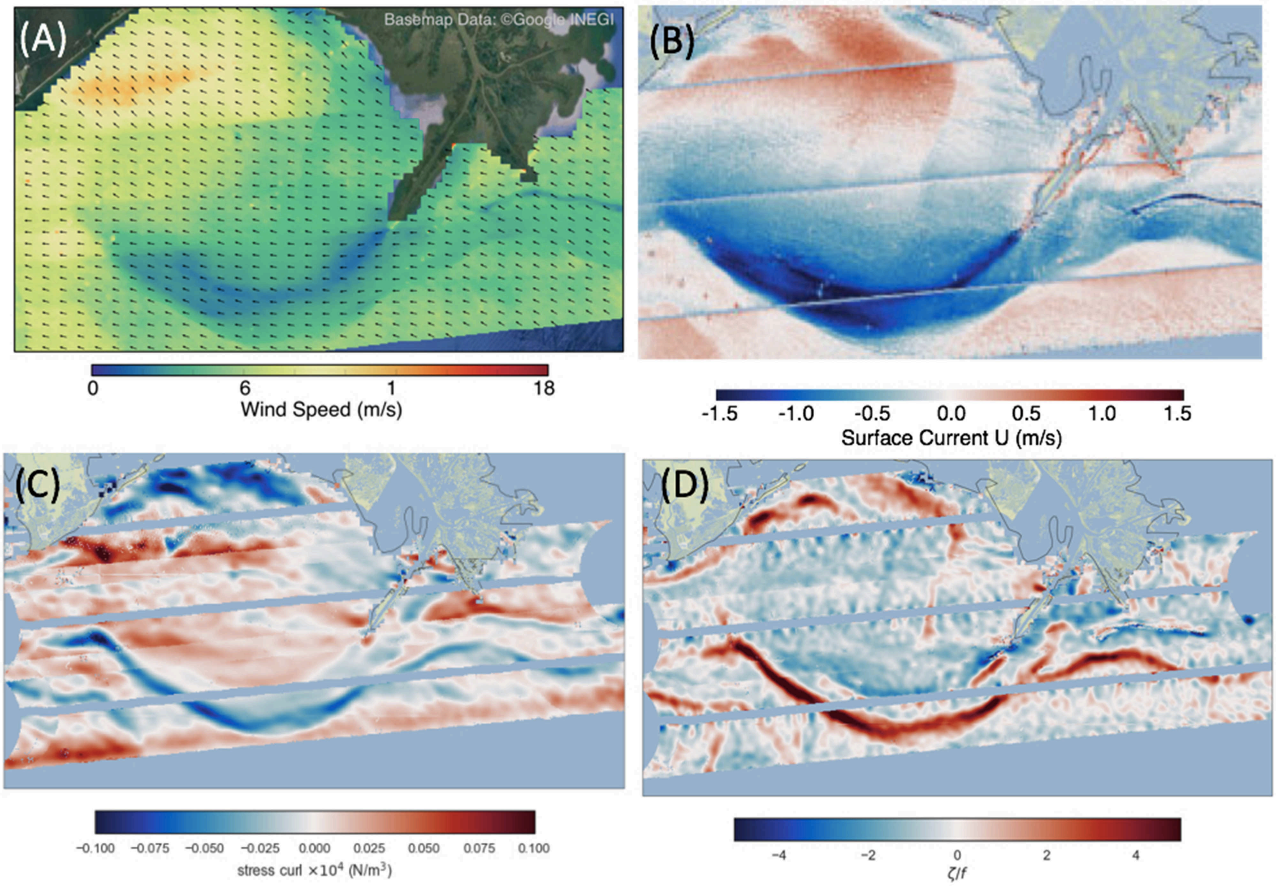

FIGURE 7 | (A) Neutral wind speed (color) and direction (arrows) from NASA DopplerScatt data over the Mississippi River plume and Barataria Bay, USA; **(B)** eastward surface current component for the same region; **(C)** wind stress curl computed from neutral winds; **(D)** surface current relative vorticity divided by the Coriolis parameter *f* computed from DopplerScatt surface currents. Note the negative correlation between **(C,D)**, as expected from Equation (2).

4. DISCOVERY: TAKING DOPPLER OCEANOGRAPHY TO SPACE

Following early airborne and space-borne demonstrations of line-of-sight surface current retrieval using interferometric radars (Goldstein et al., 1989; Romeiser, 2013) and the systematic interpretation of surface velocity from the Doppler centroid of a single SAR system (Chapron et al., 2005) into wave and current contributions, it is now well-understood that all-phase related measurements measure the same velocity. This velocity is usually a weighted-mean surface velocity, where the weight is related to the local backscatter, with the possible addition of the intrinsic scatterer velocities (Romeiser et al., 2014; Nouguier et al., 2018; Rodriguez, 2018). As a result, the measured velocity combines currents and waves, and has a sensitivity to the near-surface current shear, which varies with the choice of radar wavelength and incidence angle. A possible proxy for wave-related motions can be derived from the surface wind vector (Mouche et al., 2008; Martin et al., 2016), although this is less accurate for the near-nadir incidence angles (Ardhuin et al., 2018; Nouguier et al., 2018). This understanding has been supported by recent platform-based and airborne measurements (Rodriguez, 2018; Yurovsky et al., 2018). Many efforts have been devoted to the development of satellite systems able to measure both components of the vector currents rather than a single component in the cross-track direction.

Three satellite mission concepts that could measure surface currents in the coming decade are now at various stages of development, although none of them are so far confirmed. The SKIM mission (Ardhuin et al., 2018), pre-selected along with the Far-Infrared Outgoing Radiation (FORUM) in response to the ESA Earth Explorer 9 call, has a potential launch scheduled for 2025. Detailed design studies will lead to the final selection (either SKIM or FORUM) by September 2019. The SEASTAR mission was one of 21 mission concepts proposed in 2018 to the ESA Earth Explorer 10 call for mission ideas (Gommenginger et al., 2018) and, while not selected by ESA for EE10, continues to be promoted for implementation through other avenues and opportunities within ESA, Europe and beyond. The WaCM (WaCM, Bourassa et al., 2016; Rodriguez et al., 2018), listed in the 2017 US Decadal Survey, would address one of the seven priority areas highlighted by the U.S. National Academy of Sciences, of which three are expected to be implemented as explorer missions by NASA.

These three missions concepts all have different objectives and use different designs, leading to different products, performance expectations and sampling. SEASTAR is based on the principle of SAR Along-Track Interferometry (ATI), which was already demonstrated from space on the space shuttle and with Tandem-X, but with the difference that SEASTAR features two pairs of radar beams "squinted", respectively 45° fore and aft of the satellite, enabling measurements of the surface motion in two orthogonal directions from which, with the help of a third dual-polarized beam in the broadside direction, both current vector and wind vector can be derived. In its present inception, SEASTAR provides current vector and wind vector products at 1 km resolution over a single continuous swath of 170 km, and a random noise performance for current vectors better than 10 cm s^{-1} and 10° at 1 km resolution. Details about SEASTAR can be found in the OceanObs'19 mini-review by Gommenginger (2019) associated with this paper.

SKIM and WaCM are rotating pencil-beam sensors that provide a diversity of look directions and thus provide the two current vector components. For WaCM and SKIM instruments, the velocity is estimated by measuring the phase between pulse pairs, which, as in the ATI case, is proportional to the Doppler centroid (DC) of scatterers within the real-aperture radar footprint. The pulse-pair and ATI methods would essentially measure the same velocity (Romeiser, 2013; Rodriguez et al., 2018), but with differing noise levels. The variability of surface velocities in the real-aperture footprint is greater, since footprints are on the order of kilometers in the azimuth direction, while the azimuth footprint size is on the order of 100 m, due to wave motion. The greater Doppler variability in the real-aperture techniques results in greater noise (all other things being equal) relative to the ATI technique. Details about SKIM and WaCM can be found in the OceanObs'19 mini-reviews by Ardhuin (2019) and by Rodriguez (2019) associated with the present review.

Whereas SEASTAR seeks to achieve a resolution of 1 km or finer, WaCM and SKIM are planned to estimate currents at 25 km or greater scales, once data are averaged to yield an appropriate noise level. One drawback of the SEASTAR approach is the high power and data downlink requirements, which under the programmatic constraints of the ESA Earth Explorer 10 call, led to limiting data acquisitions to coastal, shelf and polar seas and a few open ocean sites of special interest, with a revisit time between 1 and 30 day at 45°N depending on orbital mission phase. In contrast, WaCM achieves near global coverage of both surface currents and winds in <1 day, while SKIM achieves global coverage of surface currents and waves in about 3 days at mid-latitudes. The largest difference between SKIM and WaCM is the incidence angles used for observations. SKIM is derived from the SWIM instrument flown on the China-France Ocean SATellite (CFOSAT, Hauser et al., 2017), with only a small plate rotating, carrying horns near the focal point of a fixed reflector. The SKIM technology allows incidence angles up to 12°, yielding a 6 km footprint for individual measurements over a 330 km wide swath for an orbit altitude of 850 km. Because of antenna and spin parameters, the SKIM coverage has gaps which must be filled using optimal interpolation. The interpolated data allow global coverage with a revisit time of 3 days at 45°N, at the expense of an additional mapping error. The SKIM incidence angles allow the observation of not only Doppler, but also backscatter tilt modulation, from which surface wave spectra can be estimated, as in SWIM. WaCM uses a fan-beam antenna with an incidence angle of 56°, which achieves a 2–3 km azimuth resolution and better range resolution, allowing continuous gap-less coverage over a wide 1,700–1,800 km swath (depending on the orbit) resulting measurements twice a day at 45°N. The WaCM backscatter noise level is sufficient for wind and current retrievals at resolutions better than 5 km, but the currents must be further averaged to about 25 km to achieve noise levels appropriate for surface current mapping. The engineering design for WaCM has not been finalized, and the current performance of WaCM may vary from about 6 cm s^{-1} (30 cm s^{-1}), for the low-power option, to 1.6 cm s^{-1} (8 cm s^{-1}), for the high-power option, at spatial sampling of 25 km (5 km). These sampling characteristics are important for defining the effective space-time resolution and the spatial scales that will be aliased in time.

Overall, the three proposed Doppler oceanography missions share common scientific interests but also show good levels of complementarities in terms of products, capabilities and sampling. Detailed descriptions of the performance and sampling advantages of the SEASTAR, SKIM and WaCM concepts can be found in the respective OceanObs mini-reviews by Ardhuin (2019), Gommenginger (2019), and Rodriguez (2019). It is worth remembering that, despite the high relevance and broad general interests in these issues, the exciting opportunities afforded by recent technological advances, and the high level of apparent effort expended on each concept, none of these concepts is presently approved to proceed with implementation.

5. SUMMARY AND RECOMMENDATIONS

Ocean surface winds, currents, and waves are essential climate variables playing a crucial role in exchanges of momentum, energy, heat, freshwater, gases, and other tracers between the ocean, atmosphere, and ice. This paper reviewed the present state of observations of these variables and outlined observational gaps that limit our current understanding of coupled processes that happen at the air-sea-ice interface as summarized below.

The mapping capability of the present constellation of satellite altimeters is limited to resolving wavelengths larger than 100 km. Even though higher resolution (10s of kilometers) might be achieved with SWOT, the applicability of altimeters is restricted to geostrophic flows. Total ocean surface current measurements (geostrophic and ageostrophic) at mesoscales (30–300 km) are needed to constrain heat and freshwater budgets in equatorial regions as well as the pathways of floating material and cross-shelf transport of tracers. An accuracy of 10 cm/s at 30 km spatial grid every 10 days would allow a considerable reduction in air-sea flux residuals and surface transport pathways. In addition, the momentum transfer between the atmosphere and the ocean via surface stress depends on the difference between the total surface current and surface wind vector; thus joint measurements of these variables are essential for assessing the impacts of currents in modulating the wind stress and for quantifying the energy input from the wind.

The dynamics governing surface currents and air-sea interactions dramatically change at scales smaller than 10 km (submesoscale). Apart from HFR stations, which are only available in some areas and restricted to regions inshore of 300 km, there is currently no means of systematically monitoring ocean currents at these scales. High-resolution measurements of surface currents (1–10 km) are necessary to understand processes linked to frontogenesis, cross-shelf flows associated with upwelling/downwelling, and river plume outflows. Additionally, the variability of surface waves at these scales is largely explained by wave-current interactions and dominated by the variability of the surface current field. Joint high-resolution wind, current, and wave observations are needed in order to assess the impact of wave-current interactions on extreme sea states and marine and coastal hazards.

In coastal regions, high-resolution (scales under 25 km) and high-frequency (more frequent than 4 times per day) measurements of winds, currents, and waves are necessary to resolve the details of the land-sea breeze, which impacts the sea surface temperature, stratification, and upper-ocean mixing. Furthermore, at these scales, winds associated with orographic features modulate the surface current and surface wave fields, with implications for upwelling of nutrients, transport of larvae, recreation, and navigation. A main conclusion of the inaugural Mooers Coastal Ocean and Atmosphere Prediction Workshop was that simultaneous, global satellite-based measurements of winds and currents have great potential to improve forecasting for the coastal ocean (Samelson, 2019).

Surface gravity waves are a primary source of turbulence in the upper ocean. Yet, ocean models represent unresolved processes that control vertical mixing through parameterization schemes that often do not explicitly take into account the effects of surface waves. Global observations of the 2D wave spectrum are key for constraining the parameter space in schemes of Langmuir turbulence. Another fundamental problem in the ocean-atmosphere boundary layer is the modulation of the surface wind stress by surface waves. Sea state-dependent parameterizations of air-sea fluxes lead to significant differences in the atmospheric state. Measurements of directional wave spectra along with surface currents and winds are essential information to improve empirical relationships for the drag coefficient and improve bulk formulae. It is also worth noting that wave-induced Stokes drift velocities generally exceed Ekman currents at the sea surface and are important for constraining Lagrangian pathways, impacting the transport of tracers, plastic, oil, and debris.

From a modeling perspective, a priority of the coming decade must be to better integrate ocean, wave, and atmospheric models to enable accurate observational constraint propagation between components in a forecasting or reanalysis system. Components of this system will still need to be parameterized, but these parameterizations can be improved by including estimates of the sea state.

In marginal ice zones (MIZs), measurements of sea-ice drift, surface currents, and surface waves are needed to address questions regarding freshwater fluxes and interactions between eddies and floes. Further, the directional spectrum of surface waves in polar regions is necessary to address wave-ice interactions, more specifically, wave dissipation by sea-ice.

The most fundamental idea that summarizes this review lies in the concept that surface winds, currents, and waves are coupled variables and hence require integrated observations and modeling. Future Doppler oceanography satellite concepts discussed here (i.e., SKIM, WaCM, and SEASTAR) have the potential to help fill in some of the identified observational gaps and to deliver systematic and global joint observations of surface winds, currents, and waves. The first step toward this direction was taken with the recent launch of CFOSAT, which will provide simultaneous measurements of surface winds and waves in the upcoming months. We believe that much can be learned from additional air-sea flux observational campaigns carried out in different sea state conditions in support of upcoming satellite missions. Understanding the physics of processes that mediate air-sea exchanges will lay the groundwork for incorporating their effects into model parameterizations, fostering the development of coupled wave-ocean-atmosphere-ice models. Integrated observations of these variables will facilitate the validation of such models. In a climate change scenario, better knowledge of the air-sea interactions and upper-ocean dynamics will be important for adaptation and mitigation in response to extreme events and environmental disasters.

AUTHOR CONTRIBUTIONS

AV led the conceptualization, writing, and editing of the paper. FA, AA, MB, PB, BC, BDC, JF, MF, BF-K, SG, CG, PH, MH, QL, MM, SM, AM, MR, ER, JS, AS, ET, MT, CU, and EvS have contributed equally to writing sections and revising the manuscript. All authors have approved the submitted version.

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REFERENCES

Adams, K., Barth, J., and Shearman, R. (2016). Intraseasonal cross-shelf variability of hypoxia along the Newport, Oregon, hydrographic line. *J. Phys. Oceanogr.* 46, 2219–2238. doi: 10.1175/JPO-D-15-0119.1

Akan, Ç., Moghimi, S., Özkan-Haller, H. T., Osborne, J., and Kurapov, A. (2017). On the dynamics of the Mouth of the Columbia River: results from a three-dimensional fully coupled wave-current interaction model. *J. Geophys. Res. Oceans* 122, 5218–5236. doi: 10.1002/2016JC012307

Aksenov, Y., Popova, E. E., Yool, A., Nurser, A. G., Williams, T. D., Bertino, L., et al. (2017). On the future navigability of Arctic sea routes: high-resolution projections of the Arctic Ocean and sea ice. *Mar. Policy* 75, 300–317. doi: 10.1016/j.marpol.2015.12.027

Alford, M. H. (2010). Sustained, full-water-column observations of internal waves and mixing near Mendocino Escarpment. *J. Phys. Oceanogr.* 40, 2643–2660. doi: 10.1175/2010JPO4502.1

Alford, M. H., MacKinnon, J. A., Simmons, H. L., and Nash, J. D. (2016). Near-inertial internal gravity waves in the ocean. *Annu. Rev. Mar. Sci.* 8, 95–123. doi: 10.1146/annurev-marine-010814-015746

Alpers, W., Zhang, B., Mouche, A., Zeng, K., and Chan, P. W. (2016). Rain footprints on C-band synthetic aperture radar images of the ocean–revisited. *Rem. Sens. Environ.* 187, 169–185. doi: 10.1016/j.rse.2016.10.015

Andersen, O. B., Stenseng, L., Piccioni, G., and Knudsen, P. (2016). "The DTU15 MSS (mean sea surface) and DTU15LAT (lowest astronomical tide) reference surface," in *ESA Living Planet Symposium 2016* (Prague).

Anderson, C. R., Brzezinski, M. A., Washburn, L., and Kudela, R. (2006). Circulation and environmental conditions during a toxigenic *Pseudo-nitzschia australis* bloom in the Santa Barbara Channel, California. *Mar. Ecol. Progr. Series* 327, 119–133. doi: 10.3354/meps327119

Ardhuin, F. (2019). SKIM, a candidate satellite mission exploring global ocean currents and waves. *Front. Mar. Sci.* 6:209. doi: 10.3389/fmars.2019.00209

Ardhuin, F., Aksenov, Y., Benetazzo, A., Bertino, L., Brandt, P., Caubet, E., et al. (2018). Measuring currents, ice drift, and waves from space: the Sea surface KInematics Multiscale monitoring (SKIM) concept. *Ocean Sci.* 14, 337–354. doi: 10.5194/os-14-337-2018

Ardhuin, F., Gille, S. T., Menemenlis, D., Rocha, C. B., Rascle, N., Chapron, B., et al. (2017a). Small-scale open ocean currents have large effects on wind wave heights. *J. Geophys. Res. Oceans* 122, 4500–4517. doi: 10.1002/2016JC012413

Ardhuin, F., and Jenkins, A. D. (2006). On the interaction of surface waves and upper ocean turbulence. *J. Phys. Oceanogr.* 36, 551–557. doi: 10.1175/JPO2862.1

Ardhuin, F., Rogers, E., Babanin, A. V., Filipot, J.-F., Magne, R., Roland, A., et al. (2010). Semiempirical dissipation source functions for ocean waves. Part I: definition, calibration, and validation. *J. Phys. Oceanogr.* 40, 1917–1941. doi: 10.1175/2010JPO4324.1

Ardhuin, F., Stopa, J., Chapron, B., Collard, F., Smith, M., Thomson, J., et al. (2017b). Measuring ocean waves in sea ice using SAR imagery: a quasi-deterministic approach evaluated with Sentinel-1 and *in situ* data. *Rem. Sens. Environ.* 189, 211–222. doi: 10.1016/j.rse.2016.11.024

Ardhuin, F., Stopa, J. E., Chapron, B., Collard, F., Husson, R., Jensen, R. E., et al. (2019). Observing sea states. *Front. Mar. Sci.* 6:124. doi: 10.3389/fmars.2019.00124

Aristizábal, M. F., Fewings, M. R., and Washburn, L. (2016). Contrasting spatial patterns in the diurnal and semidiurnal temperature variability in the Santa Barbara Channel, California. *J. Geophys. Res. Oceans* 121, 427–440. doi: 10.1002/2015JC011239

Aristizábal, M. F., Fewings, M. R., and Washburn, L. (2017). Effects of the relaxation of upwelling-favorable winds on the diurnal and semidiurnal water temperature fluctuations in the Santa Barbara Channel, California. *J. Geophys. Res. Oceans* 122, 7958–7977. doi: 10.1002/2017JC013199

Armitage, T. W., Bacon, S., Ridout, A. L., Petty, A. A., Wolbach, S., and Tsamados, M. (2017). Arctic Ocean surface geostrophic circulation 2003–2014. *Cryosphere* 11, 1767–1780. doi: 10.5194/tc-11-1767-2017

Armitage, T. W., Bacon, S., Ridout, A. L., Thomas, S. F., Aksenov, Y., and Wingham, D. J. (2016). Arctic sea surface height variability and change from satellite radar altimetry and GRACE, 2003–2014. *J. Geophys. Res. Oceans* 121, 4303–4322. doi: 10.1002/2015JC011579

Atlas, D. (1994). Origin of storm footprints on the sea seen by synthetic aperture radar. *Science* 266, 1364–1366. doi: 10.1126/science.266.5189.1364

Atlas, R., Hoffman, R., Leidner, S., Sienkiewicz, J., Yu, T.-W., Bloom, S., et al. (2001). The effects of marine winds from scatterometer data on weather analysis and forecasting. *Bull. Am. Meteorol. Soc.* 82, 1965–1990. doi: 10.1175/1520-0477(2001)082<1965:TEOMWF>2.3.CO;2

Atlas, R., Hoffman, R. N., Ardizzone, J., Leidner, S. M., Jusem, J. C., Smith, D. K., et al. (2011). A cross-calibrated, multiplatform ocean surface wind velocity product for meteorological and oceanographic applications. *Bull. Am. Meteorol. Soc.* 92, 157–174. doi: 10.1175/2010BAMS2946.1

Austin, J. (1999). The role of the alongshore wind stress in the heat budget of the North Carolina inner shelf. *J. Geophys. Res.* 104, 18187–18204. doi: 10.1029/1998JC900122

Babanin, A. V. (2006). On a wave-induced turbulence and a wave-mixed upper ocean layer. *Geophys. Res. Lett.* 33:L20605. doi: 10.1029/2006GL027308

Bachman, S. D., Fox-Kemper, B., Taylor, J. R., and Thomas, L. (2017). Parameterization of frontal symmetric instabilities. I: theory for resolved fronts. *Ocean Modell.* 109, 72–95. doi: 10.1016/j.ocemod.2016.12.003

Ballarotta, M., Ubelmann, C., Pujol, M.-I., Taburet, G., Legeais, J.-F., Faugere, Y., et al. (2019). On the resolution of ocean altimetry maps. *Ocean Sci.* 156. doi: 10.5194/os-2018-156

Banas, N. S., Hickey, B. M., MacCready, P., and Newton, J. A. (2004). Dynamics of Willapa Bay, Washington: a highly unsteady, partially mixed estuary. *J. Phys. Oceanogr.* 34, 2413–2427. doi: 10.1175/JPO2637.1

Barrick, D. E., Evans, M., and Weber, B. (1977). Ocean surface currents mapped by radar. *Science* 198, 138–144. doi: 10.1126/science.198.4313.138

Beal, R. C. (1980). *The Seasat SAR Wind and Ocean Wave Monitoring Capabilities: A Case Study for Pass 1339M*. APL Tech. Rep. S1R 79U-019. Laurel, MD: Johns Hopkins University.

Belcher, S. E., Grant, A. L., Hanley, K. E., Fox-Kemper, B., Van Roekel, L., Sullivan, P. P., et al. (2012). A global perspective on Langmuir turbulence in the ocean surface boundary layer. *Geophys. Res. Lett.* 39:L18605. doi: 10.1029/2012GL052932

Belcher, S. E., Hewitt, H. T., Beljaars, A., Brun, E., Fox-Kemper, B., Lemieux, J.-F., et al. (2015). "Ocean–waves–sea ice–atmosphere interactions," in *Seamless Prediction of the Earth System: From Minutes to Months*, eds G. Brunet, S. Jones, and P. M. Ruti (Geneva: World Meteorological Organization, 2015).

Bjerknes, J. (1969). Atmospheric teleconnections from the equatorial pacific. *Monthly Weather Rev.* 97, 163–172. doi: 10.1175/1520-0493(1969)097<0163:ATFTEP>2.3.CO;2

Bonjean, F., and Lagerloef, G. S. (2002). Diagnostic model and analysis of the surface currents in the tropical Pacific Ocean. *J. Phys. Oceanogr.* 32, 2938–2954. doi: 10.1175/1520-0485(2002)032<2938:DMAAOT>2.0.CO;2

Bourassa, M., Meissner, T., Cerovecki, I., Chang, P., Dong, X., De Chiara, G., et al. (2019). Remotely sensed winds and wind stresses for marine forecasting and ocean modeling. *Front. Mar. Sci.* 9:443. doi: 10.3389/fmars.2019.00443

Bourassa, M. A., Rodriguez, E., and Chelton, D. (2016). "Winds and currents mission: ability to observe mesoscale AIR/SEA coupling," in *Geoscience and Remote Sensing Symposium (IGARSS), 2016 IEEE International* (Beijing: IEEE), 7392–7395.

Boutin, G., Ardhuin, F., Dumont, D., Sévigny, C., Girard-Ardhuin, F., and Accensi, M. (2018). Floe size effect on wave-ice interactions: possible effects, implementation in wave model, and evaluation. *J. Geophys. Res. Oceans* 123, 4779–4805. doi: 10.1029/2017JC013622

Bowen, M. M., Emery, W. J., Wilkin, J. L., Tildesley, P. C., Barton, I. J., and Knewtson, R. (2002). Extracting multiyear surface currents from sequential thermal imagery using the maximum cross-correlation technique. *J. Atmos. Ocean. Technol.* 19, 1665–1676. doi: 10.1175/1520-0426(2002)019<1665:EMSCFS>2.0.CO;2

Brandt, P., Funk, A., Hormann, V., Dengler, M., Greatbatch, R. J., and Toole, J. M. (2011). Interannual atmospheric variability forced by the deep equatorial Atlantic Ocean. *Nature* 473:497. doi: 10.1038/nature10013

Brannigan, L., Marshall, D. P., Naveira Garabato, A., and Nurser, A. G. (2015). The seasonal cycle of submesoscale flows. *Ocean Modell.* 92, 69–84. doi: 10.1016/j.ocemod.2015.05.002

Brink, K. H. (2016a). Continental shelf baroclinic instability. Part I: Relaxation from upwelling or downwelling. *J. Phys. Oceanogr.* 46, 551–568. doi: 10.1175/JPO-D-15-0047.1

Brink, K. H. (2016b). Cross-shelf exchange. *Annu. Rev. Mar. Sci.* 8, 59–78. doi: 10.1146/annurev-marine-010814-015717

Brink, K. H. (2017). Surface cooling, winds, and eddies over the continental shelf. *J. Phys. Oceanogr.* 47, 879–894. doi: 10.1175/JPO-D-16-0196.1

Brink, K. H., and Cherian, D. A. (2013). Instability of an idealized tidal mixing front: symmetric instabilities and frictional effects. *J. Mar. Res.* 71, 425–450. doi: 10.1357/002224013812587582

Brink, K. H., and Seo, H. (2016). Continental shelf baroclinic instability. Part II: oscillating wind forcing. *J. Phys. Oceanogr.* 46, 569–582. doi: 10.1175/JPO-D-15-0048.1

Brown, R. A. (1980). Longitudinal instabilities and secondary flows in the planetary boundary layer: a review. *Rev. Geophys.* 18, 683–697. doi: 10.1029/RG018i003p00683

Brown, R. A. (1986). On a satellite scatterometer as an anemometer. *J. Geophys. Res.* 91, 2221–2232. doi: 10.1029/JC091iC02p02221

Caldeira, R. M. A., Marchesiello, P., Nezlin, N. P., DiGiacomo, P. M., and McWilliams, J. C. (2005). Island wakes in the Southern California Bight. *J. Geophys. Res.* 110:90. doi: 10.1029/2004JC002675

Callies, J., Ferrari, R., Klymak, J. M., and Gula, J. (2015). Seasonality in submesoscale turbulence. *Nat. Commun.* 6:6862. doi: 10.1038/ncomms7862

Cardellach, E., Fabra, F., Nogués-Correig, O., Oliveras, S., Ribó, S., and Rius, A. (2011). GNSS-R ground-based and airborne campaigns for ocean, land, ice, and snow techniques: application to the GOLD-RTR data sets. *Radio Sci.* 46, 1–16. doi: 10.1029/2011RS004683

Carr, J. R., Stokes, C., and Vieli, A. (2014). Recent retreat of major outlet glaciers on Novaya Zemlya, Russian Arctic, influenced by fjord geometry and sea-ice conditions. *J. Glaciol.* 60, 155–170. doi: 10.3189/2014JoG13J122

Caudal, G., Hauser, D., Valentin, R., and Le Gac, C. (2014). KuROS: a new airborne Ku-band Doppler radar for observation of surfaces. *J. Atmos. Ocean. Technol.* 31, 2223–2245. doi: 10.1175/JTECH-D-14-00013.1

Cavaleri, L., Fox-Kemper, B., and Hemer, M. (2012). Wind waves in the coupled climate system. *Bull. Am. Meteorol. Soc.* 93, 1651–1661. doi: 10.1175/BAMS-D-11-00170.1

Centurioni, L., Braasch, L., Di Lauro, E., Contestabile, P., De Leo, F., Casotti, R., et al. (2017). A new strategic wave measurement station off Naples port main breakwater. *Coast. Eng. Proc.* 1:36. doi: 10.9753/icce.v35.waves.36

Chan, F., Barth, J. A., Lubchenco, J., Kirincich, A., Weeks, H., Peterson, W. T., et al. (2008). Emergence of anoxia in the California Current large marine ecosystem. *Science* 319:920. doi: 10.1126/science.1149016

Chapman, D. C., and Beardsley, R. C. (1989). On the origin of shelf water in the Middle Atlantic Bight. *J. Phys. Oceanogr.* 19, 384–391. doi: 10.1175/1520-0485(1989)019<0384:OTOOSW>2.0.CO;2

Chapron, B., Collard, F., and Ardhuin, F. (2005). Direct measurements of ocean surface velocity from space: interpretation and validation. *J. Geophys. Res. Oceans* 110:C07008. doi: 10.1029/2004JC002809

Chapron, B., Collard, F., and Kerbaol, V. (2004). "Satellite synthetic aperture radar sea surface doppler measurements," in *2nd Workshop on Coastal and Marine Applications of Synthetic Aperture Radar* (Svalbard), 133–141.

Chavez, F. P., and Messié, M. (2009). A comparison of eastern boundary upwelling ecosystems. *Progr. Oceanogr.* 83, 80–96. doi: 10.1016/j.pocean.2009.07.032

Chelton, D. (2001). *Report of the High-Resolution Ocean Topography Science Working Group Meeting*. Oregon State University, College of Oceanic and Atmospheric Sciences.

Chelton, D. B., Deszoeke, R. A., Schlax, M. G., El Naggar, K., and Siwertz, N. (1998). Geographical variability of the first baroclinic Rossby radius of deformation. *J. Phys. Oceanogr.* 28, 433–460. doi: 10.1175/1520-0485(1998)028<0433:GVOTFB>2.0.CO;2

Chelton, D. B., Freilich, M. H., Sienkiewicz, J. M., and Von Ahn, J. M. (2006). On the use of QuikSCAT scatterometer measurements of surface winds for marine weather prediction. *Monthly Weather Rev.* 134, 2055–2071. doi: 10.1175/MWR3179.1

Chelton, D. B., Gaube, P., Schlax, M. G., Early, J. J., and Samelson, R. M. (2011). The influence of nonlinear mesoscale eddies on near-surface oceanic chlorophyll. *Science* 334, 328–332. doi: 10.1126/science.1208897

Chelton, D. B., Schlax, M. G., Freilich, M. H., and Milliff, R. F. (2004). Satellite measurements reveal persistent small-scale features in ocean winds. *Science* 303, 978–983. doi: 10.1126/science.1091901

Chelton, D. B., Schlax, M. G., and Samelson, R. M. (2007). Summertime coupling between sea surface temperature and wind stress in the California current system. *J. Phys. Oceanogr.* 37, 495–517. doi: 10.1175/JPO3025.1

Chelton, D. B., and Xie, S.-P. (2010). Coupled ocean-atmosphere interaction at oceanic mesoscales. *Oceanography* 23, 52–69. doi: 10.5670/oceanog.2010.05

Chen, C. (2003). Wind-induced, cross-frontal exchange on Georges Bank: a mechanism for early summer on-bank biological particle transport. *J. Geophys. Res.* 108:589. doi: 10.1029/2002JC001358

Chen, C.-T. A., Huang, T.-H., Chen, Y.-C., Bai, Y., He, X., and Kang, Y. (2013). Air–sea exchanges of CO_2 in the world's coastal seas. *Biogeosciences* 10, 6509–6544. doi: 10.5194/bg-10-6509-2013

Chen, S.-Y., and Chen, S.-N. (2017). Generation of upwelling circulation under downwelling-favorable wind within bottom-attached, buoyant coastal currents. *J. Phys. Oceanogr.* 47, 2499–2519. doi: 10.1175/JPO-D-16-0271.1

Cherian, D. A. (2016). *When an eddy encounters shelf-slope topography* (PhD thesis), Cambridge, MA: Massachusetts Institute of Technology.

Cherian, D. A., and Brink, K. H. (2016). Offshore transport of shelf water by deep-ocean eddies. *J. Phys. Oceanogr.* 46, 3599–3621. doi: 10.1175/JPO-D-16-0085.1

Cherian, D. A., and Brink, K. H. (2018). Shelf flows forced by deep-ocean anticyclonic eddies at the shelf break. *J. Phys. Oceanogr.* 48, 1117–1138. doi: 10.1175/JPO-D-17-0237.1

Clarizia, M., Gommenginger, C., Gleason, S., Srokosz, M., Galdi, C., and Di Bisceglie, M. (2009). Analysis of GNSS-R delay-Doppler maps from the UK-DMC satellite over the ocean. *Geophys. Res. Lett.* 36:L02608. doi: 10.1029/2008GL036292

Colbert, D. B. (2010). *Field Evaluation of Ocean Wave Measurement With GPS Buoys*. Technical report. Monterey, CA: Department of Oceanography, Naval Postgraduate School.

Collard, F., Ardhuin, F., and Chapron, B. (2009). Monitoring and analysis of ocean swell fields from space: new methods for routine observations. *J. Geophys. Res. Oceans* 114:C07023. doi: 10.1029/2008JC005215

Connolly, T. P., Hickey, B. M., Geier, S. L., and Cochlan, W. P. (2010). Processes influencing seasonal hypoxia in the northern California current system. *J. Geophys. Res.* 115:C03021. doi: 10.1029/2009JC005283

Connolly, T. P., and Lentz, S. J. (2014). Interannual variability of wintertime temperature on the inner continental shelf of the Middle Atlantic Bight. *J. Geophys. Res. Oceans* 119, 6269–6285. doi: 10.1002/2014JC010153

Cook, T., Hazard, L., Otero, M., and Zelenke, B. (2008). *Deployment and Maintenance of a High-Frequency Radar for Ocean Surface Current Mapping: Best Practices*. San Diego, CA: Coastal Observing Research and Development Center. Available online at: http://cordc.ucsd.edu/projects/mapping/documents/SCCOOS-BestPractices.pdf

Cornillon, P., and Park, K.-A. (2001). Warm core ring velocities inferred from NSCAT. *Geophys. Res. Lett.* 28, 575–578. doi: 10.1029/2000GL011487

Cornuelle, B., Chereskin, T., Niiler, P., Morris, M., and Musgrave, D. (2000). Observations and modeling of a California undercurrent eddy. *J. Geophys. Res. Oceans* 105, 1227–1243. doi: 10.1029/1999JC900284

Cowen, R. K., and Sponaugle, S. (2009). Larval dispersal and marine population connectivity. *Annu. Rev. Mar. Sci.* 1, 443–466. doi: 10.1146/annurev.marine.010908.163757

Cowton, T., Sole, A., Nienow, P., Slater, D., and Christoffersen, P. (2018). Linear response of east Greenland's tidewater glaciers to ocean/atmosphere warming. *Proc. Natl. Acad. Sci. U.S.A.* 115, 7907–7912. doi: 10.1073/pnas.1801769115

Criales, M. M., Cherubin, L. M., and Browder, J. A. (2015). Modeling larval transport and settlement of pink shrimp in South Florida: dynamics of behavior and tides. *Mar. Coast. Fish.* 7, 148–176. doi: 10.1080/19425120.2014.1001541

Crombie, D. D. (1955). Doppler spectrum of sea echo at 13.56 Mc./s. *Nature* 175:681. doi: 10.1038/175681a0

Dai, A., and Deser, C. (1999). Diurnal and semidiurnal variations in global surface wind and divergence fields. *J. Geophys. Res. Atmos.* 104, 31109–31125. doi: 10.1029/1999JD900927

Dai, A., and Trenberth, K. E. (2004). The diurnal cycle and its depiction in the community climate system model. *J. Clim.* 17, 930–951. doi: 10.1175/1520-0442(2004)017<0930:TDCAID>2.0.CO;2

D'Asaro, E. A. (1985). The energy flux from the wind to near-inertial motions in the surface mixed layer. *J. Phys. Oceanogr.* 15, 1043–1059. doi: 10.1175/1520-0485(1985)015<1043:TEFFTW>2.0.CO;2

D'Asaro, E. A. (2001). Turbulent vertical kinetic energy in the ocean mixed layer. *J. Phys. Oceanogr.* 31, 3530–3537. doi: 10.1175/1520-0485(2002)031<3530:TVKEIT>2.0.CO;2

D'Asaro, E. A. (2014). Turbulence in the upper-ocean mixed layer. *Annu. Rev. Mar. Sci.* 6, 101–115. doi: 10.1146/annurev-marine-010213-135138

D'Asaro, E. A., Lee, C., Rainville, L., Thomas, L., and Harcourt, R. (2011). Enhanced turbulence and energy dissipation at ocean fronts. *Science* 332:1201515. doi: 10.1126/science.1201515

D'Asaro, E. A., Sanford, T. B., Niiler, P. P., and Terrill, E. J. (2007). Cold wake of hurricane Frances. *Geophys. Res. Lett.* 34:L15609. doi: 10.1029/2007GL030160

D'Asaro, E. A., Shcherbina, A. Y., Klymak, J. M., Molemaker, J., Novelli, G., Guigand, C. M., et al. (2018). Ocean convergence and the dispersion of flotsam. *Proc. Natl. Acad. Sci. U.S.A.* 115:201718453. doi: 10.1073/pnas.1718453115

De Vries, J., Waldron, J., and Cunningham, V. (2003). Field tests of the new Datawell DWR-G GPA wave buoy. *Sea Technol.* 44, 50–55. Available online at: http://datawell.nl/Portals/0/Documents/Publications/datawell_publication_dwr-g_seatechnology-dec2003_2003-12-01.pdf

Deike, L., Melville, W. K., and Popinet, S. (2016). Air entrainment and bubble statistics in breaking waves. *J. Fluid Mech.* 801, 91–129. doi: 10.1017/jfm.2016.372

Dewar, W., and Flierl, G. (1987). Some effects of the wind on rings. *J. Phys. Oceanogr.* 17, 1653–1667. doi: 10.1175/1520-0485(1987)017<1653:SEOTWO>2.0.CO;2

Doble, M. J., and Bidlot, J.-R. (2013). Wave buoy measurements at the Antarctic sea ice edge compared with an enhanced ECMWF WAM: progress towards global waves-in-ice modelling. *Ocean Modell.* 70, 166–173. doi: 10.1016/j.ocemod.2013.05.012

Doble, M. J., Wilkinson, J. P., Valcic, L., Robst, J., Tait, A., Preston, M., et al. (2017). Robust wavebuoys for the marginal ice zone: experiences from a large persistent array in the Beaufort Sea. *Elem. Sci. Anth.* 5:47. doi: 10.1525/elementa.233

Donato, T. F., and Marmorino, G. O. (2002). The surface morphology of a coastal gravity current. *Cont. Shelf Res.* 22, 141–146. doi: 10.1016/S0278-4343(01)00066-8

Donelan, M. A., Dobson, F. W., Smith, S. D., and Anderson, R. J. (1993). On the dependence of sea surface roughness on wave development. *J. Phys. Oceanogr.* 23, 2143–2149. doi: 10.1175/1520-0485(1993)023<2143:OTDOSS>2.0.CO;2

Dong, C., Chen, D., and Ou, H.-W. (2015). Numerical study on tidally induced cross-frontal mean circulation. *Atmos. Ocean* 53, 363–375. doi: 10.1080/07055900.2015.1056082

Dorman, C. E., Mejia, J., Koračin, D., and McEvoy, D. (2017). "Worldwide marine fog occurrence and climatology," in *Marine Fog: Challenges and Advancements in Observations, Modeling, and Forecasting*, eds D. Koračin, and C. E. Dorman (Cham: Springer International Publishing), 7–152.

Dotto, T. S., Naveira Garabato, A. C., Bacon, S., Tsamados, M., Holland, P. R., Hooley, J., et al. (2018). Variability of the Ross Gyre, Southern Ocean: drivers and responses revealed by satellite altimetry. *Geophys. Res. Lett.* 45, 6195–6204. doi: 10.1029/2018GL078607

Drake, P. T., Edwards, C. A., Morgan, S. G., and Dever, E. P. (2013). Influence of larval behavior on transport and population connectivity in a realistic simulation of the California Current System. *J. Mar. Res.* 71, 317–350. doi: 10.1357/002224013808877099

Dumbauld, B. R., Kauffman, B. E., Trimble, A. C., and Ruesink, J. L. (2011). The Willapa Bay oyster reserves in Washington State: fishery collapse, creating a sustainable replacement, and the potential for habitat conservation and restoration. *J. Shellfish Res.* 30, 71–83. doi: 10.2983/035.030.0111

Dumont, D., Kohout, A., and Bertino, L. (2011). A wave-based model for the marginal ice zone including a floe breaking parameterization. *J. Geophys. Res. Oceans* 116:C04001. doi: 10.1029/2010JC006682

Edson, J. B., Jampana, V., Weller, R. A., Bigorre, S. P., Plueddemann, A. J., Fairall, C. W., et al. (2013). On the exchange of momentum over the open ocean. *J. Phys. Oceanogr.* 43, 1589–1610. doi: 10.1175/JPO-D-12-0173.1

Edwards, K. A., Rogers, D. P., and Dorman, C. E. (2002). Adjustment of the marine atmospheric boundary layer to the large-scale bend in the California coast. *J. Geophys. Res.* 107:3213. doi: 10.1029/2001JC000807

Elipot, S., Lumpkin, R., Perez, R. C., Lilly, J. M., Early, J. J., and Sykulski, A. M. (2016). A global surface drifter data set at hourly resolution. *J. Geophys. Res. Oceans* 121, 2937–2966. doi: 10.1002/2016JC011716

Ellenson, A., and Özkan-Haller, H. T. (2018). Predicting large ocean wave events characterized by bimodal energy spectra in the presence of a low-level southerly wind feature. *Weather Forecast.* e0035.1. doi: 10.1175/WAF-D-17-0035.1

Fan, Y., and Griffies, S. M. (2014). Impacts of parameterized Langmuir turbulence and nonbreaking wave mixing in global climate simulations. *J. Clim.* 27, 4752–4775. doi: 10.1175/JCLI-D-13-00583.1

Feltham, D. L. (2008). Sea ice rheology. *Annu. Rev. Fluid Mech.* 40, 91–112. doi: 10.1146/annurev.fluid.40.111406.102151

Feng, H., Vandemark, D., and Wilkin, J. (2016). Gulf of Maine salinity variation and its correlation with upstream Scotian shelf currents at seasonal and interannual time scales. *J. Geophys. Res. Oceans* 121, 8585–8607. doi: 10.1002/2016JC012337

Fewings, M. R. (2017). Large-scale structure in wind forcing over the California current system in summer. *Monthly Weather Rev.* 145, 4227–4247. doi: 10.1175/MWR-D-17-0106.1

Fewings, M. R., and Lentz, S. J. (2010). Momentum balances on the inner continental shelf at Martha's Vineyard Coastal Observatory. *J. Geophys. Res.* 115:C12023. doi: 10.1029/2009JC005578

Fewings, M. R., and Lentz, S. J. (2011). Summertime cooling of the shallow continental shelf. *J. Geophys. Res.* 116:C07015. doi: 10.1029/2010JC006744

Fewings, M. R., Lentz, S. J., and Fredericks, J. (2008). Observations of cross-shelf flow driven by cross-shelf winds over the inner continental shelf. *J. Phys. Oceanogr.* 38, 2358–2378. doi: 10.1175/2008JPO3990.1

Fewings, M. R., Washburn, L., Dorman, C. E., Gotschalk, C., and Lombardo, K. (2016). Synoptic forcing of wind relaxations at Pt. Conception, California. *J. Geophys. Res. Oceans* 121, 5711–5730. doi: 10.1002/2016JC011699

Fewings, M. R., Washburn, L., and Ohlmann, J. C. (2015). Coastal water circulation patterns around the Northern Channel Islands and Point Conception, California. *Progr. Oceanogr.* 138, 283–304. doi: 10.1016/j.pocean.2015.10.001

Flynn, K. R., Fewings, M. R., Gotschalk, C., and Lombardo, K. (2017). Large-scale anomalies in sea-surface temperature and air-sea fluxes during wind relaxation events off the United States West Coast in summer. *J. Geophys. Res. Oceans* 122, 2574–2594. doi: 10.1002/2016JC012613

Fois, F., Hoogeboom, P., Le Chevalier, F., Stoffelen, A., and Mouche, A. (2015). DopSCAT: a mission concept for simultaneous measurements of marine winds and surface currents. *J. Geophys. Res. Oceans* 120, 7857–7879. doi: 10.1002/2015JC011011

Foltz, G. R., and McPhaden, M. J. (2008). Impact of Saharan dust on tropical North Atlantic SST. *J. Clim.* 21, 5048–5060. doi: 10.1175/2008JCLI2232.1

Foltz, G. R., Schmid, C., and Lumpkin, R. (2018). An enhanced PIRATA dataset for tropical Atlantic Ocean–atmosphere research. *J. Clim.* 31, 1499–1524. doi: 10.1175/JCLI-D-16-0816.1

Fong, D. A., and Geyer, R. W. (2001). Response of a river plume during an upwelling favorable wind event. *J. Geophys. Res. Oceans* 106, 1067–1084. doi: 10.1029/2000JC900134

Fong, D. A., and Geyer, W. R. (2002). The alongshore transport of freshwater in a surface-trapped river plume. *J. Phys. Oceanogr.* 32, 957–972. doi: 10.1175/1520-0485(2002)032<0957:TATOFI>2.0.CO;2

Foster, R. C. (2005). Why rolls are prevalent in the hurricane boundary layer. *J. Atmos. Sci.* 62, 2647–2661. doi: 10.1175/JAS3475.1

Foti, G., Gommenginger, C., Jales, P., Unwin, M., Shaw, A., Robertson, C., et al. (2015). Spaceborne GNSS reflectometry for ocean winds: first results from the UK TechDemoSat-1 mission. *Geophys. Res. Lett.* 42, 5435–5441. doi: 10.1002/2015GL064204

Foti, G., Gommenginger, C., and Srokosz, M. (2017). First spaceborne GNSS-reflectometry observations of hurricanes from the UK TechDemoSat-1 mission. *Geophys. Res. Lett.* 44, 12358–12366. doi: 10.1002/2017GL076166

Fox-Kemper, B., Bachman, S., Pearson, B., and Reckinger, S. (2014). Principles and advances in subgrid modelling for eddy-rich simulations. *Clivar Exchanges* 65, 42–46. Available online at: http://bit.ly/1qSMTzA

Fox-Kemper, B., Danabasoglu, G., Ferrari, R., Griffies, S., Hallberg, R., Holland, M., et al. (2011). Parameterization of mixed layer eddies. III: implementation and impact in global ocean climate simulations. *Ocean Modell.* 39, 61–78. doi: 10.1016/j.ocemod.2010.09.002

Fram, J., Stewart, H., Brzezinski, M., Gaylord, B., Reed, D., Williams, S., et al. (2008). Physical pathways and utilization of nitrate supply to the giant kelp, *Macrocystis pyrifera*. *Limnol. Oceanogr.* 53, 1589–1603. doi: 10.4319/lo.2008.53.4.1589

Fraser, C. I., Morrison, A. K., Hogg, A. M., Macaya, E. C., van Sebille, E., Ryan, P. G., et al. (2018). Antarctica's ecological isolation will be broken by storm-driven dispersal and warming. *Nat. Clim. Change* 8:704. doi: 10.1038/s41558-018-0209-7

Fratantoni, P. S., and Pickart, R. S. (2007). The western North Atlantic shelfbreak current system in summer. *J. Phys. Oceanogr.* 37, 2509–2533. doi: 10.1175/JPO3123.1

Frenger, I., Gruber, N., Knutti, R., and Münnich, M. (2013). Imprint of southern ocean eddies on winds, clouds and rainfall. *Nat. Geosci.* 6:608. doi: 10.1038/ngeo1863

Fu, L.-L., and Glazman, R. (1991). The effect of the degree of wave development on the sea state bias in radar altimetry measurement. *J. Geophys. Res. Oceans* 96, 829–834. doi: 10.1029/90JC02319

Fu, L. L., and Holt, B. (1982). *Seasat Views Oceans and Seas With Synthetic Aperture Radar*. Tech. Rep. JPL Publ. 81–102. Pasadena, CA: Jet Propulsion Laboratory, California Institute of Technology.

Fujimura, A. G., Reniers, A. J., Paris, C. B., Shanks, A. L., MacMahan, J. H., and Morgan, S. G. (2014). Numerical simulations of larval transport into a rip-channeled surf zone. *Limnol. Oceanogr.* 59, 1434–1447. doi: 10.4319/lo.2014.59.4.1434

Garcia Berdeal, I., Hickey, B. M., and Kawase, M. (2002). Influence of wind stress and ambient flow on a high discharge river plume. *J. Geophys. Res. Oceans* 107, 13–11. doi: 10.1029/2001JC000932

García-Medina, G., Özkan-Haller, H. T., Ruggiero, P., and Oskamp, J. (2013). An inner-shelf wave forecasting system for the US Pacific Northwest. *Weather Forecast.* 28, 681–703. doi: 10.1175/WAF-D-12-00055.1

García-Reyes, M., and Largier, J. (2010). Observations of increased wind-driven coastal upwelling off central California. *J. Geophys. Res. Oceans* 115:C04011. doi: 10.1029/2009JC005576

Garratt, J. (1977). Review of drag coefficients over oceans and continents. *Monthly Weather Rev.* 105, 915–929. doi: 10.1175/1520-0493(1977)105<0915:RODCOO>2.0.CO;2

Garrison, J. L., Katzberg, S. J., and Hill, M. I. (1998). Effect of sea roughness on bistatically scattered range coded signals from the global positioning system. *Geophys. Res. Lett.* 25, 2257–2260. doi: 10.1029/98GL51615

Gaube, P., Chelton, D. B., Samelson, R. M., Schlax, M. G., and O'Neill, L. W. (2015). Satellite observations of mesoscale eddy-induced Ekman pumping. *J. Phys. Oceanogr.* 45, 104–132. doi: 10.1175/JPO-D-14-0032.1

Gaube, P., McGillicuddy, D. J., Chelton, D. B., Behrenfeld, M. J., and Strutton, P. G. (2014). Regional variations in the influence of mesoscale eddies on near-surface chlorophyll. *J. Geophys. Res. Oceans* 119, 8195–8220. doi: 10.1002/2014JC010111

Gawarkiewicz, G., McCarthy, R. K., Barton, K., Masse, A. K., and Church, T. M. (1990). A Gulf Stream-derived pycnocline intrusion on the Middle Atlantic Bight shelf. *J. Geophys. Res. Oceans* 95, 22305–22313. doi: 10.1029/JC095iC12p22305

Gawarkiewicz, G., Monismith, S., and Largier, J. (2007). Observing larval transport processes affecting population connectivity: progress and challenges. *Oceanography* 20, 40–53. doi: 10.5670/oceanog.2007.28

Gentemann, C. L., Minnett, P. J., and Ward, B. (2009). Profiles of ocean surface heating (POSH): a new model of upper ocean diurnal warming. *J. Geophys. Res. Oceans* 114:C07017. doi: 10.1029/2008JC004825

Gerbi, G. P., Chant, R. J., and Wilkin, J. L. (2013). Breaking surface wave effects on river plume dynamics during upwelling-favorable winds. *J. Phys. Oceanogr.* 43, 1959–1980. doi: 10.1175/JPO-D-12-0185.1

Gerling, T. W. (1986). Structure of the surface wind field from the Seasat SAR. *J. Geophys. Res.* 91, 2308–2320. doi: 10.1029/JC091iC02p02308

Giglio, D., Gille, S. T., Subramanian, A. C., and Nguyen, S. (2017). The role of wind gusts in upper ocean diurnal variability. *J. Geophys. Res. Oceans* 122, 7751–7764. doi: 10.1002/2017JC012794

Giles, K. A., Laxon, S. W., Ridout, A. L., Wingham, D. J., and Bacon, S. (2012). Western Arctic Ocean freshwater storage increased by wind-driven spin-up of the Beaufort Gyre. *Nat. Geosci.* 5:194. doi: 10.1038/ngeo1379

Gille, S. T., Llewellyn Smith, S. G., and Lee, S. M. (2003). Measuring the sea breeze from QuikSCAT scatterometry. *Geophys. Res. Lett.* 30:1114. doi: 10.1029/2002GL016230

Gille, S. T., Llewellyn Smith, S. G., and Statom, N. M. (2005). Global observations of the land breeze. *Geophys. Res. Lett.* 32:L05605. doi: 10.1029/2004GL022139

Gimbert, F., Marsan, D., Weiss, J., Jourdain, N. C., and Barnier, B. (2012). Sea ice inertial oscillations in the Arctic Basin. *Cryosphere* 6, 1187–1201. doi: 10.5194/tc-6-1187-2012

Goldstein, R., Zebker, H., and Barnett, T. (1989). Remote sensing of ocean currents. *Science* 246, 1282–1285. doi: 10.1126/science.246.4935.1282

Gommenginger, C. (2019). SEASTAR: a mission to study ocean submesoscale dynamics and small- scale atmosphere-ocean processes in coastal, shelf and polar seas. *Front. Mar. Sci.* 601. doi: 10.13140/RG.2.2.20415.61601

Gommenginger, C., Chapron, B., Martin, A., Marquez, J., Brownsword, C., and Buck, C. (2018). "SEASTAR: a new mission for high-resolution imaging of ocean surface current and wind vectors from space," in *EUSAR 2018; 12th European Conference on Synthetic Aperture Radar* (Aachen: VDE), 1–4.

González-Haro, C., Autret, E., Isern-Fontanet, J., Tandeo, P., and Garello, R. (2016). "Ocean surface current reconstruction: on the transfer function between infrared SST and along-track altimeter observations," in *OCEANS 2016 MTS/IEEE Monterey* (Monterey, CA: IEEE), 1–5.

Grachev, A., Fairall, C., Hare, J., Edson, J., and Miller, S. (2003). Wind stress vector over ocean waves. *J. Phys. Oceanogr.* 33, 2408–2429. doi: 10.1175/1520-0485(2003)033<2408:WSVOOW>2.0.CO;2

Graham, W. M., and Largier, J. L. (1997). Upwelling shadows as nearshore retention sites: the example of northern Monterey Bay. *Cont. Shelf Res.* 17, 509–532. doi: 10.1016/S0278-4343(96)00045-3

Grant, A. L., and Belcher, S. E. (2009). Characteristics of Langmuir turbulence in the ocean mixed layer. *J. Phys. Oceanogr.* 39, 1871–1887. doi: 10.1175/2009JPO4119.1

Grantham, B. A., Chan, F., Nielsen, K. J., Fox, D. S., Barth, J. A., Huyer, A., et al. (2004). Upwelling-driven nearshore hypoxia signals ecosystem and oceanographic changes in the northeast Pacific. *Nature* 429, 749–754. doi: 10.1038/nature02605

Gula, J., Molemaker, M. J., and McWilliams, J. C. (2014). Submesoscale cold filaments in the Gulf Stream. *J. Phys. Oceanogr.* 44, 2617–2643. doi: 10.1175/JPO-D-14-0029.1

Hackerott, J. A., Pezzi, L. P., Paskyabi, M. B., Oliveira, A. P., Reuder, J., de Souza, R. B., et al. (2018). The role of roughness and stability on the momentum flux in the marine atmospheric surface layer: a study on the southwestern atlantic ocean. *J. Geophys. Res. Atmos.* 123, 3914–3932. doi: 10.1002/2017JD027994

Haine, T. W., and Marshall, J. (1998). Gravitational, symmetric, and baroclinic instability of the ocean mixed layer. *J. Phys. Oceanogr.* 28, 634–658. doi: 10.1175/1520-0485(1998)028<0634:GSABIO>2.0.CO;2

Hales, B., Karp-Boss, L., Perlin, A., and Wheeler, P. A. (2006). Oxygen production and carbon sequestration in an upwelling coastal margin. *Glob. Biogeochem. Cycles* 20:GB3001. doi: 10.1029/2005GB002517

Hales, B., Takahashi, T., and Bandstra, L. (2005). Atmospheric CO_2 uptake by a coastal upwelling system. *Glob. Biogeochem. Cycles* 19:GB1009. doi: 10.1029/2004GB002295

Hall, C., and Cordey, R. (1988). "Multistatic scatterometry," in *International Geoscience and Remote Sensing Symposium, 1988. IGARSS'88. Remote Sensing: Moving Toward the 21st Century*, Vol. 1 (Edinburgh: IEEE), 561–562.

Halpern, D. (2002). Offshore Ekman transport and Ekman pumping off Peru during the 1997–1998 El Nino. *Geophys. Res. Lett.* 29, 19-1–19-4. doi: 10.1029/2001GL014097

Hanafin, J. A., Quilfen, Y., Ardhuin, F., Sienkiewicz, J., and Queffeulou, P. (2012). Phenomenal sea states and swell from a North Atlantic Storm in February 2011: a comprehensive. *Geophys. Res. Lett* 36:L06607. doi: 10.1175/BAMS-D-11-00128.1

Haney, S., Fox-Kemper, B., Julien, K., and Webb, A. (2015). Symmetric and geostrophic instabilities in the wave-forced ocean mixed layer. *J. Phys. Oceanogr.* 45, 3033–3056. doi: 10.1175/JPO-D-15-0044.1

Harcourt, R. R. (2013). A second-moment closure model of Langmuir turbulence. *J. Phys. Oceanogr.* 43, 673–697. doi: 10.1175/JPO-D-12-0105.1

Harcourt, R. R. (2015). An improved second-moment closure model of Langmuir turbulence. *J. Phys. Oceanogr.* 45, 84–103. doi: 10.1175/JPO-D-14-0046.1

Harcourt, R. R., and D'Asaro, E. A. (2008). Large-eddy simulation of Langmuir turbulence in pure wind seas. *J. Phys. Oceanogr.* 38, 1542–1562. doi: 10.1175/2007JPO3842.1

Harlan, J., Terrill, E., Hazard, L., Keen, C., Barrick, D., Whelan, C., et al. (2010). The integrated ocean observing system high-frequency radar network: status and local, regional, and national applications. *Mar. Technol. Soc. J.* 44, 122–132. doi: 10.4031/MTSJ.44.6.6

Hasager, C. B., Mouche, A., Badger, M., Bingol, F., Karagali, I., Driesenaar, T., et al. (2015). Offshore wind climatology based on synergetic use of Envisat ASAR, ASCAT and QuikSCAT. *Rem. Sens. Environ.* 156, 247–263. doi: 10.1016/j.rse.2014.09.030

Hasselmann, K. F., Chapron, B., Aouf, L., Ardhuin, F., Collard, F., Engen, G., et al. (2013). The ERS SAR wave mode: a breakthrough in global ocean wave observations. *ESA Commun.* 1326, 167–197.

Hauser, D., Tison, C., Amiot, T., Delaye, L., Corcoral, N., and Castillan, P. (2017). SWIM: the first spaceborne wave scatterometer. *IEEE Trans. Geosci. Rem. Sens.* 55, 3000–3014. doi: 10.1109/TGRS.2017.2658672

Hendrickson, J., and MacMahan, J. (2009). Diurnal sea breeze effects on inner-shelf cross-shore exchange. *Cont. Shelf Res.* 29, 2195–2206. doi: 10.1016/j.csr.2009.08.011

Heorton, H. D., Feltham, D. L., and Hunt, J. C. (2014). The response of the sea ice edge to atmospheric and oceanic jet formation. *J. Phys. Oceanogr.* 44, 2292–2316. doi: 10.1175/JPO-D-13-0184.1

Herbers, T., Jessen, P., Janssen, T., Colbert, D., and MacMahan, J. (2012). Observing ocean surface waves with GPS-tracked buoys. *J. Atmos. Ocean. Technol.* 29, 944–959. doi: 10.1175/JTECH-D-11-00128.1

Hetland, R. D. (2017). Suppression of baroclinic instabilities in buoyancy-driven flow over sloping bathymetry. *J. Phys. Oceanogr.* 47, 49–68. doi: 10.1175/JPO-D-15-0240.1

Hibler, W., Hutchings, J., and Ip, C. (2006). Sea-ice arching and multiple flow states of Arctic pack ice. *Ann. Glaciol.* 44, 339–344. doi: 10.3189/172756406781811448

Hickey, B., Geier, S., Kachel, N., and MacFadyen, A. (2005). A bi-directional river plume: the Columbia in summer. *Cont. Shelf Res.* 25, 1631–1656. doi: 10.1016/j.csr.2005.04.010

Holland, P. R., and Kwok, R. (2012). Wind-driven trends in Antarctic sea-ice drift. *Nat. Geosci.* 5:872. doi: 10.1038/ngeo1627

Horvat, C., Tziperman, E., and Campin, J.-M. (2016). Interaction of sea ice floe size, ocean eddies, and sea ice melting. *Geophys. Res. Lett.* 43, 8083–8090. doi: 10.1002/2016GL069742

Horwitz, R., and Lentz, S. J. (2014). Inner-shelf response to cross-shelf wind stress: the importance of the cross-shelf density gradient in an idealized numerical model and field observations. *J. Phys. Oceanogr.* 44, 86–103. doi: 10.1175/JPO-D-13-075.1

Horwitz, R. M., and Lentz, S. J. (2016). The effect of wind direction on cross-shelf transport on an initially stratified inner shelf. *J. Mar. Res.* 74, 201–227. doi: 10.1357/002224016820870648

Houghton, R. W., and Ho, C. (2001). Diapycnal flow through the Georges Bank tidal front: a dye tracer study. *Geophys. Res. Lett.* 28, 33–36. doi: 10.1029/2000GL012298

Hristov, T., Miller, S., and Friehe, C. (2003). Dynamical coupling of wind and ocean waves through wave-induced air flow. *Nature* 422:55. doi: 10.1038/nature01382

Hughes, C. W., and Wilson, C. (2008). Wind work on the geostrophic ocean circulation: an observational study of the effect of small scales in the wind stress. *J. Geophys. Res. Oceans* 113:C02016. doi: 10.1029/2007JC004371

Hummels, R., Dengler, M., Brandt, P., and Schlundt, M. (2014). Diapycnal heat flux and mixed layer heat budget within the Atlantic Cold Tongue. *Clim. Dyn.* 43, 3179–3199. doi: 10.1007/s00382-014-2339-6

Hutchings, J. K., Heil, P., and Hibler III, W. D. (2005). Modeling linear kinematic features in sea ice. *Monthly Weather Rev.* 133, 3481–3497. doi: 10.1175/MWR3045.1

Hwang, P. A., García-Nava, H., and Ocampo-Torres, F. J. (2011). Observations of wind wave development in mixed seas and unsteady wind forcing. *J. Phys. Oceanogr.* 41, 2343–2362. doi: 10.1175/JPO-D-11-044.1

Isern-Fontanet, J., Chapron, B., Lapeyre, G., and Klein, P. (2006). Potential use of microwave sea surface temperatures for the estimation of ocean currents. *Geophys. Res. Lett.* 33:L24608. doi: 10.1029/2006GL027801

Jackson, F., Walton, W., Hines, D., Walter, B., and Peng, C. (1992). Sea surface mean square slope from K u-band backscatter data. *J. Geophys. Res. Oceans* 97, 11411–11427. doi: 10.1029/92JC00766

Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., et al. (2015). Plastic waste inputs from land into the ocean. *Science* 347, 768–771. doi: 10.1126/science.1260352

Janssen, P. (2004). *The Interaction of Ocean Waves and Wind*. Cambridge: Cambridge University Press.

Jochum, M., Malanotte-Rizzoli, P., and Busalacchi, A. (2004). Tropical instability waves in the Atlantic Ocean. *Ocean Modell.* 7, 145–163. doi: 10.1016/S1463-5003(03)00042-8

Kaplan, I. C., Williams, G. D., Bond, N. A., Hermann, A. J., and Siedlecki, S. A. (2016). Cloudy with a chance of sardines: forecasting sardine distributions using regional climate models. *Fish. Oceanogr.* 25, 15–27. doi: 10.1111/fog.12131

Karp-Boss, L., Wheeler, P. A., Hales, B., and Covert, P. (2004). Distributions and variability of particulate organic matter in a coastal upwelling system. *J. Geophys. Res.* 109:C09010. doi: 10.1029/2003JC002184

Kelly, K. A., Dickinson, S., and Johnson, G. C. (2005). Comparisons of scatterometer and TAO winds reveal time-varying surface currents for the tropical Pacific Ocean. *J. Atmos. Ocean. Technol.* 22, 735–745. doi: 10.1175/JTECH1738.1

Kelly, K. A., Dickinson, S., McPhaden, M. J., and Johnson, G. C. (2001). Ocean currents evident in satellite wind data. *Geophys. Res. Lett.* 28, 2469–2472. doi: 10.1029/2000GL012610

Kim, S. Y., Terrill, E. J., Cornuelle, B. D., Jones, B., Washburn, L., Moline, M. A., et al. (2011). Mapping the US West Coast surface circulation: a multiyear analysis of high-frequency radar observations. *J. Geophys. Res. Oceans* 116:C03011. doi: 10.1029/2010JC006669

Kirincich, A., Lentz, S., and Barth, J. (2009). Wave-driven inner-shelf motions on the Oregon coast. *J. Phys. Oceanogr.* 39, 2942–2956. doi: 10.1175/2009JPO4041.1

Kirincich, A., Lentz, S. J., and Gerbi, G. P. (2010). Calculating Reynolds stresses from ADCP measurements in the presence of surface gravity waves using the cospectra-fit method. *J. Atmos. Ocean. Technol.* 27, 889–890. doi: 10.1175/2009JTECHO682.1

Kirincich, A. R., and Barth, J. A. (2009). Alongshelf variability of inner-shelf circulation along the central Oregon coast during summer. *J. Phys. Oceanogr.* 39, 1380–1398. doi: 10.1175/2008JPO3760.1

Kitaigorodsky, S. A. (1970). *The Physics of Air-Sea Interaction*. Jerusalem: Israel Program for Scientific Translations.

Koch, W. (2004). Directional analysis of SAR images aiming at wind direction. *IEEE Trans. Geosci. Rem. Sens.* 42, 702–710. doi: 10.1109/TGRS.2003.818811

Kræmer, T., Johnsen, H., Brekke, C., and Engen, G. (2018). Comparing SAR-based short time-lag cross correlation and Doppler-derived sea ice drift velocities. *IEEE Trans. Geosci. Rem. Sens.* 56, 1898–1908. doi: 10.1109/TGRS.2017.2769222

Kudryavtsev, V., and Chapron, B. (2016). On growth rate of wind waves: impact of short-scale breaking modulations. *J. Phys. Oceanogr.* 46, 349–360. doi: 10.1175/JPO-D-14-0216.1

Kudryavtsev, V., Chapron, B., and Makin, V. (2014a). Impact of wind waves on the air-sea fluxes: a coupled model. *J. Geophys. Res. Oceans* 46, 1022–1037. doi: 10.1002/2013JC009412

Kudryavtsev, V., Kozlov, I., Chapron, B., and Johannessen, J. A. (2014b). Quad-polarization SAR features of ocean currents. *J. Geophys. Res. Oceans* 119, 6046–6065. doi: 10.1002/2014JC010173

Kudryavtsev, V., Yurovskaya, M., Chapron, B., Collard, F., and Donlon, C. (2017). Sun glitter imagery of ocean surface waves. Part 1: directional spectrum retrieval and validation. *J. Geophys. Res. Oceans* 122, 1369–1383. doi: 10.1002/2016JC012425

Kuitenbrouwer, D., Reniers, A., Jamie, M., and Roth, M. K. (2018). Coastal protection by a small scale river plume against oil spills in the Northern Gulf of Mexico. *Cont. Shelf Res.* 163, 1–11. doi: 10.1016/j.csr.2018.05.002

Kukulka, T., Plueddemann, A. J., Trowbridge, J. H., and Sullivan, P. P. (2009). Significance of Langmuir circulation in upper ocean mixing: Comparison of observations and simulations. *Geophys. Res. Lett.* 36:L10603. doi: 10.1029/2009GL037620

Kwok, R., and Morison, J. (2011). Dynamic topography of the ice-covered Arctic Ocean from ICESat. *Geophys. Res. Lett.* 38:L02501. doi: 10.1029/2010GL046063

Kwok, R., Schweiger, A., Rothrock, D., Pang, S., and Kottmeier, C. (1998). Sea ice motion from satellite passive microwave imagery assessed with ERS SAR and buoy motions. *J. Geophys. Res. Oceans* 103, 8191–8214. doi: 10.1029/97JC03334

LaCasce, J. (2008). Statistics from Lagrangian observations. *Progr. Oceanogr.* 77, 1–29. doi: 10.1016/j.pocean.2008.02.002

Laruelle, G. G., Lauerwald, R., Pfeil, B., and Regnier, P. (2014). Regionalized global budget of the CO_2 exchange at the air-water interface in continental shelf seas. *Glob. Biogeochem. Cycles* 28, 1199–1214. doi: 10.1002/2014GB004832

Laurindo, L. C., Mariano, A. J., and Lumpkin, R. (2017). An improved near-surface velocity climatology for the global ocean from drifter observations. *Deep Sea Res.* 124, 73–92. doi: 10.1016/j.dsr.2017.04.009

Lavrenov, I. (2013). *Wind-Waves in Oceans: Dynamics and Numerical Simulations*. Berlin: Springer Science & Business Media.

Law, K. L. (2017). Plastics in the marine environment. *Annu. Rev. Mar. Sci.* 9, 205–229. doi: 10.1146/annurev-marine-010816-060409

Law, K. L., Morét-Ferguson, S., Maximenko, N. A., Proskurowski, G., Peacock, E. E., Hafner, J., et al. (2010). Plastic accumulation in the North Atlantic subtropical gyre. *Science* 329, 1185–1188. doi: 10.1126/science.1192321

Law, K. L., Morét-Ferguson, S. E., Goodwin, D. S., Zettler, E. R., DeForce, E., Kukulka, T., et al. (2014). Distribution of surface plastic debris in the eastern Pacific Ocean from an 11-year data set. *Environ. Sci. Technol.* 48, 4732–4738. doi: 10.1021/es4053076

Le Quéré, C., Andrew, R. M., Friedlingstein, P., Sitch, S., Pongratz, J., Manning, A. C., et al. (2017). Global carbon budget 2017. *Earth Syst. Sci. Data* 10, 405–448. doi: 10.5194/essd-10-405-2018

Lebreton, L. C., Van der Zwet, J., Damsteeg, J.-W., Slat, B., Andrady, A., and Reisser, J. (2017). River plastic emissions to the world's oceans. *Nat. Commun.* 8:15611. doi: 10.1038/ncomms15611

Lee, D.-K., and Centurioni, L. (2018). Water following characteristics of Global Drifter Program drifters with and without subsurface float. *Deep Sea Res.* 137, 20–29. doi: 10.1016/j.dsr.2018.05.003

Lee, T., and Liu, W. T. (2005). Effects of high-frequency wind sampling on simulated mixed layer depth and upper ocean temperature. *J. Geophys. Res. Oceans* 110:C05002. doi: 10.1029/2004JC002746

Lentz, S. J. (2004). The response of buoyant coastal plumes to upwelling-favorable winds. *J. Phys. Oceanogr.* 34, 2458–2469. doi: 10.1175/JPO2647.1

Lentz, S. J. (2010). The mean along-isobath heat and salt balances over the Middle Atlantic Bight continental shelf. *J. Phys. Oceanogr.* 40, 934–948. doi: 10.1175/2009JPO4214.1

Lentz, S. J., Elgar, S., and Guza, R. T. (2003). Observations of the flow field near the nose of a buoyant coastal current. *J. Phys. Oceanogr.* 33, 933–943. doi: 10.1175/1520-0485(2003)33<933:OOTFFN>2.0.CO;2

Lentz, S. J., and Fewings, M. R. (2012). The wind- and wave-driven inner-shelf circulation. *Annu. Rev. Mar. Sci.* 4, 317–343. doi: 10.1146/annurev-marine-120709-142745

Lentz, S. J., Fewings, M. R., Howd, P., Fredericks, J., and Hathaway, K. (2008). Observations and a model of undertow over the inner continental shelf. *J. Phys. Oceanogr.* 38, 2341–2357. doi: 10.1175/2008JPO3986.1

Lentz, S. J., and Largier, J. (2006). The influence of wind forcing on the Chesapeake Bay buoyant coastal current. *J. Phys. Oceanogr.* 36, 1305–1316. doi: 10.1175/JPO2909.1

Li, Q., and Fox-Kemper, B. (2017). Assessing the effects of Langmuir turbulence on the entrainment buoyancy flux in the ocean surface boundary layer. *J. Phys. Oceanogr.* 47, 2863–2886. doi: 10.1175/JPO-D-17-0085.1

Li, Q., Webb, A., Fox-Kemper, B., Craig, A., Danabasoglu, G., Large, W. G., et al. (2016). Langmuir mixing effects on global climate: WAVEWATCH III in CESM. *Ocean Modell.* 103, 145–160. doi: 10.1016/j.ocemod.2015.07.020

Li, X.-M., Lehner, S., and Bruns, T. (2011). Ocean wave integral parameter measurements using Envisat ASAR wave mode data. *IEEE Trans. Geosci. Rem. Sens.* 49, 155–174. doi: 10.1109/TGRS.2010.2052364

Liang, J.-H., Deutsch, C., McWilliams, J. C., Baschek, B., Sullivan, P. P., and Chiba, D. (2013). Parameterizing bubble-mediated air-sea gas exchange and its effect on ocean ventilation. *Glob. Biogeochem. Cycles* 27, 894–905. doi: 10.1002/gbc.20080

Liu, T. W., Xie, X., and Niiler, P. P. (2007). Ocean–atmosphere interaction over Agulhas Extension meanders. *J. Clim.* 20, 5784–5797. doi: 10.1175/2007JCLI1732.1

Loder, J. W., Brickman, D., and Horne, E. P. W. (1992). Detailed structure of currents and hydrography on the northern side of Georges Bank. *J. Geophys. Res.* 97:14331. doi: 10.1029/92JC01342

Loder, J. W., and Wright, D. G. (1985). Tidal rectification and frontal circulation on the sides of Georges Bank. *J. Mar. Res.* 43, 581–604. doi: 10.1357/002224085788440367

Longuet-Higgins, M. S., Cartwright, D. E., and Smith, N. D. (1963). "Observations of the directional spectrum of sea waves using the motions of a floating buoy," in *Ocean Wave Spectra, Proceedings of a Conference, Easton, Maryland* (Upper Saddle River, NJ: National Academy of Sciences, Prentice-Hall), 111–136.

Lough, R. G., and Manning, J. P. (2001). Tidal-front entrainment and retention of fish larvae on the southern flank of Georges Bank. *Deep-Sea Res.* 48, 631–644. doi: 10.1016/S0967-0645(00)00130-2

Lumpkin, R., and Johnson, G. C. (2013). Global ocean surface velocities from drifters: mean, variance, El Niño–southern oscillation response, and seasonal cycle. *J. Geophys. Res. Oceans* 118, 2992–3006. doi: 10.1002/jgrc.20210

Lumpkin, R., Özgökmen, T., and Centurioni, L. (2017). Advances in the application of surface drifters. *Annu. Rev. Mar. Sci.* 9, 59–81. doi: 10.1146/annurev-marine-010816-060641

Lumpkin, R., and Pazos, M. (2007). "Measuring surface currents with surface velocity program drifters: the instrument, its data, and some recent results," in *Lagrangian Analysis and Prediction of Coastal and Ocean Dynamics*, eds A. Griffa, A. D. Kirwan, A. J. Mariano, T. Özgökmen, and H. T. Rossby (Cambridge, UK: Cambridge University Press), 39–67.

Luo, H., Bracco, A., Cardona, Y., and McWilliams, J. C. (2016). Submesoscale circulation in the northern Gulf of Mexico: surface processes and the impact of the freshwater river input. *Ocean Modell.* 101, 68–82. doi: 10.1016/j.ocemod.2016.03.003

Lygre, A., and Krogstad, H. E. (1986). Maximum entropy estimation of the directional distribution in ocean wave spectra. *J. Phys. Oceanogr.* 16, 2052–2060. doi: 10.1175/1520-0485(1986)016<2052:MEEOTD>2.0.CO;2

MacKinnon, J., St Laurent, L., and Naveira Garabato, A. C. (2013). Diapycnal mixing processes in the ocean interior. *Int. Geophys.* 103, 159–183. doi: 10.1016/B978-0-12-391851-2.00007-6

MacKinnon, J. A., Zhao, Z., Whalen, C. B., Waterhouse, A. F., Trossman, D. S., Sun, O. M., et al. (2017). Climate process team on internal wave–driven ocean mixing. *Bull. Am. Meteorol. Soc.* 98, 2429–2454. doi: 10.1175/BAMS-D-16-0030.1

Makin, V. K. (2008). On the possible impact of a following-swell on the atmospheric boundary layer. *Bound. Layer Meteorol.* 129, 469–478. doi: 10.1007/s10546-008-9320-z

Marcq, S., and Weiss, J. (2012). Influence of sea ice lead-width distribution on turbulent heat transfer between the ocean and the atmosphere. *Cryosphere* 6, 143–156. doi: 10.5194/tc-6-143-2012

Martin, A. C., Gommenginger, C., Marquez, J., Doody, S., Navarro, V., and Buck, C. (2016). Wind-wave-induced velocity in ATI SAR ocean surface currents: first experimental evidence from an airborne campaign. *J. Geophys. Res. Oceans* 121, 1640–1653. doi: 10.1002/2015JC011459

Matano, R. P., Palma, E. D., and Piola, A. R. (2010). The influence of the Brazil and Malvinas Currents on the Southwestern Atlantic shelf circulation. *Ocean Sci.* 6, 983–995. doi: 10.5194/os-6-983-2010

Maximenko, N., Hafner, J., and Niiler, P. (2012). Pathways of marine debris derived from trajectories of Lagrangian drifters. *Mar. Pollut. Bull.* 65, 51–62. doi: 10.1016/j.marpolbul.2011.04.016

Maximenko, N., Niiler, P., Centurioni, L., Rio, M.-H., Melnichenko, O., Chambers, D., et al. (2009). Mean dynamic topography of the ocean derived from satellite and drifting buoy data using three different techniques. *J. Atmos. Ocean. Technol.* 26, 1910–1919. doi: 10.1175/2009JTECHO672.1

McPhee-Shaw, E., Siegel, D., Washburn, L., Brzezinski, M., Jones, J., Leydecker, A., et al. (2007). Mechanisms for nutrient delivery to the inner shelf: observations from the Santa Barbara Channel. *Limnol. Oceanogr.* 52, 1748–1766. doi: 10.4319/lo.2007.52.5.1748

McWilliams, J. C. (1985). Submesoscale, coherent vortices in the ocean. *Rev. Geophys.* 23, 165–182. doi: 10.1029/RG023i002p00165

McWilliams, J. C. (2016). Submesoscale currents in the ocean. *Proc. R. Soc. A* 472:20160117. doi: 10.1098/rspa.2016.0117

McWilliams, J. C. (2017). Submesoscale surface fronts and filaments: secondary circulation, buoyancy flux, and frontogenesis. *J. Fluid Mech.* 823, 391–432. doi: 10.1017/jfm.2017.294

McWilliams, J. C., and Fox-Kemper, B. (2013). Oceanic wave-balanced surface fronts and filaments. *J. Fluid Mech.* 730, 464–490. doi: 10.1017/jfm.2013.348

McWilliams, J. C., Huckle, E., Liang, J., and Sullivan, P. P. (2014). Langmuir turbulence in swell. *J. Phys. Oceanogr.* 44, 870–890. doi: 10.1175/JPO-D-13-0122.1

McWilliams, J. C., and Sullivan, P. P. (2000). Vertical mixing by Langmuir circulations. *Spill Sci. Technol. Bull.* 6, 225–237. doi: 10.1016/S1353-2561(01)00041-X

McWilliams, J. C., Sullivan, P. P., and Moeng, C.-H. (1997). Langmuir turbulence in the ocean. *J. Fluid Mech.* 334, 1–30. doi: 10.1017/S0022112096004375

Meissner, T., and Wentz, F. (2005). "Ocean retrievals for WindSat: radiative transfer model, algorithm, validation," in *OCEANS, 2005. Proceedings of MTS/IEEE* (Seoul: IEEE), 130–133.

Meissner, T., and Wentz, F. J. (2009). Wind-vector retrievals under rain with passive satellite microwave radiometers. *IEEE Trans. Geosci. Rem. Sens.* 47, 3065–3083. doi: 10.1109/TGRS.2009.2027012

Melville, W. K., and Rapp, R. J. (1985). Momentum flux in breaking waves. *Nature* 317, 514–516. doi: 10.1038/317514a0

Mensa, J. A., Garraffo, Z., Griffa, A., Özgökmen, T. M., Haza, A., and Veneziani, M. (2013). Seasonality of the submesoscale dynamics in the Gulf Stream region. *Ocean Dyn.* 63, 923–941. doi: 10.1007/s10236-013-0633-1

Miller, C. B., Lynch, D. R., Carlotti, F., Gentleman, W., and Lewis, C. V. W. (1998). Coupling of an individual-based population dynamic model of *Calanus finmarchicus* to a circulation model for the Georges Bank region. *Fish. Oceanogr.* 7, 219–234. doi: 10.1046/j.1365-2419.1998.00072.x

Minobe, S., Kuwano-Yoshida, A., Komori, N., Xie, S.-P., and Small, R. (2008). Influence of the Gulf Stream on the troposphere. *Nature* 452, 206–209. doi: 10.1038/nature06690

Minobe, S., Miyashita, M., Kuwano-Yoshida, A., Tokinaga, H., and Xie, S.-P. (2010). Atmospheric response to the Gulf Stream: seasonal variations. *J. Clim.* 23, 3699–3719. doi: 10.1175/2010JCLI3359.1

Monteiro, I. T., Santos, A. J., Belo-Pereira, M., and Oliveira, P. B. (2016). Adjustment of the summertime marine atmospheric boundary layer to the western Iberia coastal morphology. *J. Geophys. Res. Atmos.* 121, 3875–3893. doi: 10.1002/2016JD025055

Morrow, R., Fu, L.-L., Ardhuin, F., Benkiran, M., Chapron, B., Cosme, E., et al. (2019). Global observations of fine-scale ocean surface topography with the Surface Water and Ocean Topography (SWOT) mission. *Front. Mar. Sci.* 6:232. doi: 10.3389/fmars.2019.00232

Mouche, A., and Chapron, B. (2015). Global C-band Envisat, RADARSAT-2 and Sentinel-1 SAR measurements in co-polarization and cross-polarization. *J. Geophys. Res. Oceans* 120, 7195–7207. doi: 10.1002/2015JC011149

Mouche, A., Chapron, B., Reul, N., and Collard, F. (2008). Predicted Doppler shifts induced by ocean surface wave displacements using asymptotic electromagnetic wave scattering theories. *Waves Random Complex Media* 18, 185–196. doi: 10.1080/17455030701564644

Mouche, A., Chapron, B., Zhang, B., and Husson, R. (2017). Combined co- and cross-polarized SAR measurements under extreme wind conditions. *IEEE Trans. Geosci. Rem. Sens.* 55, 6476–6755. doi: 10.1109/TGRS.2017.2732508

Mouche, A., Collard, F., Chapron, B., Dagestad, K.-F., Guitton, G., Johannessen, J. A., et al. (2012). On the use of Doppler shift for sea surface wind retrieval from SAR. *IEEE Trans. Geosci. Rem. Sens.* 50, 2901–2909. doi: 10.1109/TGRS.2011.2174998

Mrvaljevic, R. K., Black, P. G., Centurioni, L. R., Chang, Y.-T., D'Asaro, E. A., Jayne, S. R., et al. (2013). Observations of the cold wake of Typhoon Fanapi (2010). *Geophys. Res. Lett.* 40, 316–321. doi: 10.1029/2012GL054282

Muckenhuber, S., and Sandven, S. (2017). Open-source sea ice drift algorithm for Sentinel-1 SAR imagery using a combination of feature tracking and pattern matching. *Cryosphere* 11, 1835–1850. doi: 10.5194/tc-11-1835-2017

Münchow, A., and Garvine, R. W. (1993). Buoyancy and wind forcing of a coastal current. *J. Mar. Res.* 51, 293–322. doi: 10.1357/0022240933223747

Nicholls, R. J., and Cazenave, A. (2010). Sea-level rise and its impact on coastal zones. *Science* 328, 1517–1520. doi: 10.1126/science.1185782

Notz, D., and Marotzke, J. (2012). Observations reveal external driver for Arctic sea-ice retreat. *Geophys. Res. Lett.* 39:L08502. doi: 10.1029/2012GL051094

Nouguier, F., Chapron, B., Collard, F., Mouche, A., Rascle, N., Ardhuin, F., et al. (2018). Sea surface kinematics from near-nadir radar measurements. *IEEE Trans. Geosci. Rem. Sens.* 56, 6169–6179. doi: 10.1109/TGRS.2018.2833200

Nouguier, F., Mouche, A., Rascle, N., Chapron, B., and Vandemark, D. C. (2016). Analysis of dual-frequency ocean backscatter measurements at Ku-and Ka-bands using near-nadir incidence GPM radar data. *IEEE Geosci. Rem. Sens. Lett.* 13, 1310–1314. doi: 10.1109/LGRS.2016.2583198

Nurser, A., and Bacon, S. (2014). The Rossby radius in the Arctic Ocean. *Ocean Sci.* 10, 967–975. doi: 10.5194/os-10-967-2014

Nuss, W. A., Bane, J. M., Thompson, W. T., Holt, T., Dorman, C. E., Ralph, F. M., et al. (2000). Coastally trapped wind reversals: progress toward understanding. *Bull. Am. Meteorol. Soc.* 81, 719–743. doi: 10.1175/1520-0477(2000)081<0719:CTWRPT>2.3.CO;2

Ohlmann, J. C., Fewings, M. R., and Melton, C. (2012). Lagrangian observations of inner-shelf motions in Southern California: can surface waves decelerate shoreward-moving drifters just outside the surf zone? *J. Phys. Oceanogr.* 42, 1313–1326. doi: 10.1175/JPO-D-11-0142.1

Oikkonen, A., Haapala, J., Lensu, M., Karvonen, J., and Itkin, P. (2017). Small-scale sea ice deformation during N-ICE2015: from compact pack ice to marginal ice zone. *J. Geophys. Res. Oceans* 122, 5105–5120. doi: 10.1002/2016JC012387

O'Neill, L., Chelton, D., and Esbensen, S. (2012). Covariability of surface wind and stress responses to sea surface temperature fronts. *J. Clim.* 25, 5916–5942. doi: 10.1175/JCLI-D-11-00230.1

O'Neill, L. W. (2012). Wind speed and stability effects on coupling between surface wind stress and SST observed from buoys and satellite. *J. Clim.* 25, 1544–1569. doi: 10.1175/JCLI-D-11-00121.1

O'Neill, L. W., Chelton, D. B., and Esbensen, S. K. (2003). Observations of SST-induced perturbations of the wind stress field over the Southern Ocean on seasonal timescales. *J. Clim.* 16, 2340–2354. doi: 10.1175/2780.1

O'Neill, L. W., Chelton, D. B., and Esbensen, S. K. (2010). The effects of SST-induced surface wind speed and direction gradients on midlatitude surface vorticity and divergence. *J. Clim.* 23, 255–281. doi: 10.1175/2009JCLI2613.1

O'Neill, L. W., Chelton, D. B., Esbensen, S. K., and Wentz, F. J. (2005). High-resolution satellite measurements of the atmospheric boundary layer response to SST variations along the Agulhas Return Current. *J. Clim.* 18, 2706–2723. doi: 10.1175/JCLI3415.1

Pacanowski, R. (1987). Effect of equatorial currents on surface stress. *J. Phys. Oceanogr.* 17, 833–838. doi: 10.1175/1520-0485(1987)017<0833:EOECOS>2.0.CO;2

Paduan, J. D., and Washburn, L. (2013). High-frequency radar observations of ocean surface currents. *Annu. Rev. Mar. Sci.* 5, 115–136. doi: 10.1146/annurev-marine-121211-172315

Painter, S. C., Hartman, S. E., Kivimäe, C., Salt, L. A., Clargo, N. M., Bozec, Y., et al. (2016). Carbon exchange between a shelf sea and the ocean: the Hebrides Shelf, west of Scotland. *J. Geophys. Res. Oceans* 121, 4522–4544. doi: 10.1002/2015JC011599

Pazan, S. E., and Niiler, P. P. (2001). Recovery of near-surface velocity from undrogued drifters. *J. Atmos. Ocean. Technol.* 18, 476–489. doi: 10.1175/1520-0426(2001)018<0476:RONSVF>2.0.CO;2

Peacock, N. R., and Laxon, S. W. (2004). Sea surface height determination in the Arctic Ocean from ERS altimetry. *J. Geophys. Res. Oceans* 109:C07001. doi: 10.1029/2001JC001026

Peral, E., Rodríguez, E., and Esteban-Fernández, D. (2015). Impact of surface waves on SWOT's projected ocean accuracy. *Rem. Sens.* 7, 14509–14529. doi: 10.3390/rs71114509

Perlin, N., Skyllingstad, E. D., and Samelson, R. M. (2011). Coastal atmospheric circulation around an idealized cape during wind-driven upwelling studied from a coupled ocean–atmosphere model. *Monthly Weather Rev.* 139, 809–829. doi: 10.1175/2010MWR3372.1

Phillips, O. (1984). On the response of short ocean wave components at a fixed wavenumber to ocean current variations. *J. Phys. Oceanogr.* 14, 1425–1433. doi: 10.1175/1520-0485(1984)014<1425:OTROSO>2.0.CO;2

Pineau-Guillou, L., Ardhuin, F., Bouin, M.-N., Redelsperger, J.-L., Chapron, B., Bidlot, J.-R., et al. (2018). Strong winds in a coupled wave–atmosphere model during a North Atlantic storm event: evaluation against observations. *Q. J. Royal Meteorol. Soc.* 144, 317–332. doi: 10.1002/qj.3205

Piñones, A., Castilla, J. C., Guiñez, R., and Largier, J. L. (2007). Nearshore surface temperatures in Antofagasta Bay (Chile) and adjacent upwelling centers. *Cien. Mar.* 33, 37–48. doi: 10.7773/cm.v33i1.1226

Piola, A. R., Matano, R. P., Palma, E. D., Möller, O. O. Jr., and Campos, E. J. (2005). The influence of the Plata river discharge on the western South Atlantic shelf. *Geophys. Res. Lett.* 32:L01603. doi: 10.1029/2004GL021638

Plueddemann, A., and Farrar, J. (2006). Observations and models of the energy flux from the wind to mixed-layer inertial currents. *Deep Sea Res.* 53, 5–30. doi: 10.1016/j.dsr2.2005.10.017

Pollard, R. (1973). Interpretation of near-surface current meter observations. *Deep Sea Res. Oceanogr. Abstr.* 20, 261–268. doi: 10.1016/0011-7471(73)90015-6

Poulain, P.-M., Gerin, R., Mauri, E., and Pennel, R. (2009). Wind effects on drogued and undrogued drifters in the eastern Mediterranean. *J. Atmos. Ocean. Technol.* 26, 1144–1156. doi: 10.1175/2008JTECHO618.1

Price, J. F. (1981). Upper ocean response to a hurricane. *J. Phys. Oceanogr.* 11, 153–175. doi: 10.1575/1912/10271

Pringle, J. M. (2018). Remote forcing of shelf flows by density gradients and the origin of the annual mean flow on the Mid-Atlantic Bight. *J. Geophys. Res. Oceans* 123, 4464–4482. doi: 10.1029/2017JC013721

Pringle, J. M., and Dever, E. P. (2009). Dynamics of wind-driven upwelling and relaxation between Monterey Bay and Point Arena: local-, regional-, and gyre-scale controls. *J. Geophys. Res. Oceans* 114. doi: 10.1029/2008JC005016

Pujol, M.-I., Schaeffer, P., Faugère, Y., Raynal, M., Dibarboure, G., and Picot, N. (2018). Gauging the improvement of recent mean sea surface models: a new approach for identifying and quantifying their errors. *J. Geophys. Res. Oceans* 123, 5889–5911. doi: 10.1029/2017JC013503

Qiu, B., Chen, S., Klein, P., Sasaki, H., and Sasai, Y. (2014). Seasonal mesoscale and submesoscale eddy variability along the North Pacific subtropical countercurrent. *J. Phys. Oceanogr.* 44, 3079–3098. doi: 10.1175/JPO-D-14-0071.1

Quilfen, Y., Chapron, B., Elfouhaily, T., Katsaros, K., and Tournadre, J. (1998). Observation of tropical cyclones by high-resolution scatterometry. *J. Geophys. Res. Oceans* 103, 7767–7786. doi: 10.1029/97JC01911

Quilfen, Y., Yurovskaya, M., Chapron, B., and Ardhuin, F. (2018). Storm waves focusing and steepening in the Agulhas current: Satellite observations and modeling. *Rem. Sens. Environ.* 216, 561–571. doi: 10.1016/j.rse.2018.07.020

Ràfols, L., Grifoll, M., Jordà, G., Espino, M., Sairouní, A., and Bravo, M. (2017). Shelf circulation induced by an orographic wind jet. *J. Geophys. Res. Oceans* 122, 8225–8245. doi: 10.1002/2017JC012773

Rahn, D. A., Parish, T. R., and Leon, D. (2013). Airborne measurements of coastal jet transition around Point Conception, California. *Monthly Weather Rev.* 141, 3827–3839. doi: 10.1175/MWR-D-13-00030.1

Rampal, P., Weiss, J., Dubois, C., and Campin, J.-M. (2011). IPCC climate models do not capture Arctic sea ice drift acceleration: consequences in terms of projected sea ice thinning and decline. *J. Geophys. Res. Oceans* 116:C00D07. doi: 10.1029/2011JC007110

Rascle, N., Molemaker, J., Marié, L., Nouguier, F., Chapron, B., Lund, B., et al. (2017). Intense deformation field at oceanic front inferred from directional sea surface roughness observations. *Geophys. Res. Lett.* 44, 5599–5608. doi: 10.1002/2017GL073473

Rascle, N., Nouguier, F., Chapron, B., Mouche, A., and Ponte, A. (2016). Surface roughness changes by finescale current gradients: properties at multiple azimuth view angles. *J. Phys. Oceanogr.* 46, 3681–3694. doi: 10.1175/JPO-D-15-0141.1

Regnier, P., Friedlingstein, P., Ciais, P., Mackenzie, F. T., Gruber, N., Janssens, I. A., et al. (2013). Anthropogenic perturbation of the carbon fluxes from land to ocean. *Nat. Geosci.* 6:597. doi: 10.1038/ngeo1830

Renault, L., Deutsch, C., McWilliams, J. C., Frenzel, H., Liang, J.-H., and Colas, F. (2016a). Partial decoupling of primary productivity from upwelling in the California current system. *Nat. Geosci.* 9, 505–508. doi: 10.1038/ngeo2722

Renault, L., McWilliams, J. C., and Gula, J. (2018). Dampening of submesoscale currents by air-sea stress coupling in the Californian upwelling system. *Sci. Rep.* 8:13388. doi: 10.1038/s41598-018-31602-3

Renault, L., McWilliams, J. C., and Masson, S. (2017a). Satellite observations of imprint of oceanic current on wind stress by air-sea coupling. *Sci. Rep.* 7:17747. doi: 10.1038/s41598-017-17939-1

Renault, L., McWilliams, J. C., and Penven, P. (2017b). Modulation of the Agulhas current retroflection and leakage by oceanic current interaction with the atmosphere in coupled simulations. *J. Phys. Oceanogr.* e0168.1. doi: 10.1175/JPO-D-16-0168.1

Renault, L., Molemaker, J., Gula, J., Masson, S., and McWilliams, J. (2016b). Control and stabilization of the Gulf stream by oceanic current interaction with the atmosphere. *J. Phys. Oceanogr.* 6:e0115.1. doi: 10.1175/JPO-D-16-0115.1

Renault, L., Molemaker, J., McWilliams, J., Shchepetkin, A., Lemarie, F., Chelton, D., et al. (2016c). Modulation of wind work by oceanic current interaction with the atmosphere. *J. Phys. Oceanogr.* 46, 1685–1704. doi: 10.1175/JPO-D-15-0232.1

Rennie, S. E., Largier, J. L., and Lentz, S. J. (1999). Observations of a pulsed buoyancy current downstream of Chesapeake Bay. *J. Geophys. Res.* 104, 18227–18240. doi: 10.1029/1999JC900153

Ricker, R., Girard-Ardhuin, F., Krumpen, T., and Lique, C. (2018). Satellite-derived sea ice export and its impact on Arctic ice mass balance. *Cryosphere* 12, 3017–3032. doi: 10.5194/tc-12-3017-2018

Rio, M.-H., and Hernandez, F. (2003). High-frequency response of wind-driven currents measured by drifting buoys and altimetry over the world ocean. *J. Geophys. Res. Oceans* 108:NO. C8, 3283. doi: 10.1029/2002JC001655

Rio, M.-H., Mulet, S., and Picot, N. (2014). Beyond GOCE for the ocean circulation estimate: synergetic use of altimetry, gravimetry, and *in situ* data provides new insight into geostrophic and Ekman currents. *Geophys. Res. Lett.* 41, 8918–8925. doi: 10.1002/2014GL061773

Rio, M.-H., and Santoleri, R. (2018). Improved global surface currents from the merging of altimetry and sea surface temperature data. *Rem. Sens. Environ.* 216, 770–785. doi: 10.1016/j.rse.2018.06.003

Rio, M.-H., Santoleri, R., Bourdalle-Badie, R., Griffa, A., Piterbarg, L., and Taburet, G. (2016). Improving the altimeter-derived surface currents using high-resolution sea surface temperature data: a feasability study based on model outputs. *J. Atmos. Ocean. Technol.* 33, 2769–2784. doi: 10.1175/JTECH-D-16-0017.1

Rippeth, T. P., Lincoln, B. J., Lenn, Y.-D., Green, J. M., Sundfjord, A., and Bacon, S. (2015). Tide-mediated warming of Arctic halocline by Atlantic heat fluxes over rough topography. *Nat. Geosci.* 8:191. doi: 10.1038/ngeo2350

Risien, C. M., and Strub, P. T. (2016). Blended sea level anomaly fields with enhanced coastal coverage along the U.S. West Coast. *Sci. Data* 3:160013. doi: 10.1038/sdata.2016.13

Roarty, H., Cook, T., Hazard, L., George, D., Harlan, J., Cosoli, S., et al. (2019). The global high frequency radar network. *Front. Mar. Sci.* 6:164. doi: 10.3389/fmars.2019.00164

Rodriguez, E. (2018). On the optimal design of doppler scatterometers. *Rem. Sens.* 10:1765. doi: 10.3390/rs10111765

Rodriguez, E. (2019). The winds and currents mission concept. *Front. Mar. Sci.* 438. doi: 10.3389/fmars.2019.00438

Rodriguez, E., Wineteer, A., Perkovic-Martin, D., Gal, T., Stiles, B., Niamsuwan, N., et al. (2018). Estimating ocean vector winds and currents using a Ka-band pencil-beam Doppler scatterometer. *Rem. Sens.* 10:576. doi: 10.3390/rs10040576

Rodriguez, E., and Wineteer, A. G. (2018). "Observations of submesoscale surface currents and winds with a Doppler scatterometer," in *AGU Fall Meeting Abstracts* (Washington, DC).

Rogerson, A. (1999). Transcritical flows in the coastal marine atmospheric boundary layer. *J. Atmos. Sci.* 56, 2761–2779. doi: 10.1175/1520-0469(1999)056<2761:TFITCM>2.0.CO;2

Romeiser, R. (2013). The future of SAR-based oceanography: high-resolution current measurements by along-track interferometry. *Oceanography* 26, 92–99. doi: 10.5670/oceanog.2013.37

Romeiser, R., Runge, H., Suchandt, S., Kahle, R., Rossi, C., and Bell, P. S. (2014). Quality assessment of surface current fields from TerraSAR-X and TanDEM-X along-track interferometry and Doppler centroid analysis. *IEEE Trans. Geosci. Rem. Sens.* 52, 2759–2772. doi: 10.1109/TGRS.2013.2265659

Romero, L., Lenain, L., and Melville, W. K. (2017). Observations of surface wave–current interaction. *J. Phys. Oceanogr.* 47, 615–632. doi: 10.1175/JPO-D-16-0108.1

Romero, L., and Melville, W. K. (2010). Airborne observations of fetch-limited waves in the gulf of tehuantepec. *J. Phys. Oceanogr.* 40, 441–465. doi: 10.1175/2009JPO4127.1

Roth, M. K., MacMahan, J., Reniers, A., Özgökmen, T. M., Woodall, K., and Haus, B. (2017). Observations of inner shelf cross-shore surface material transport adjacent to a coastal inlet in the northern Gulf of Mexico. *Cont. Shelf Res.* 137, 142–153. doi: 10.1016/j.csr.2016.12.017

Roughan, M. (2005a). Observations of divergence and upwelling around Point Loma, California. *J. Geophys. Res.* 110:1899. doi: 10.1029/2004JC002662

Roughan, M. (2005b). Subsurface recirculation and larval retention in the lee of a small headland: a variation on the upwelling shadow theme. *J. Geophys. Res.* 110:161. doi: 10.1029/2005JC002898

Ruf, C. S., Atlas, R., Chang, P. S., Clarizia, M. P., Garrison, J. L., Gleason, S., et al. (2016). New ocean winds satellite mission to probe hurricanes and tropical convection. *Bull. Am. Meteorol. Soc.* 97, 385–395. doi: 10.1175/BAMS-D-14-00218.1

Ryan, J., Davis, C., Tufillaro, N., Kudela, R., and Gao, B.-C. (2014). Application of the hyperspectral imager for the coastal ocean to phytoplankton ecology studies in Monterey Bay, CA, USA. *Rem. Sens.* 6, 1007–1025. doi: 10.3390/rs6021007

Ryan, J. P., Gower, J. F. R., King, S. A., Bissett, W. P., Fischer, A. M., Kudela, R. M., et al. (2008). A coastal ocean extreme bloom incubator. *Geophys. Res. Lett.* 35:L12602. doi: 10.1029/2008GL034081

Sabine, C. L., Feely, R. A., Gruber, N., Key, R. M., Lee, K., Bullister, J. L., et al. (2004). The oceanic sink for anthropogenic CO_2. *Science* 305, 367–371. doi: 10.1126/science.1097403

Samelson, R. M. (2019). Challenges and opportunities in coastal prediction. *EOS* 100. doi: 10.1029/2019EO113841

Schlitzer, R. (2002). Carbon export fluxes in the Southern Ocean: results from inverse modeling and comparison with satellite-based estimates. *Deep Sea Res.* 49, 1623–1644. doi: 10.1016/S0967-0645(02)00004-8

Schlundt, M., Brandt, P., Dengler, M., Hummels, R., Fischer, T., Bumke, K., et al. (2014). Mixed layer heat and salinity budgets during the onset of the 2011 Atlantic cold tongue. *J. Geophys. Res. Oceans* 119, 7882–7910. doi: 10.1002/2014JC010021

Scott, R. B., and Xu, Y. (2009). An update on the wind power input to the surface geostrophic flow of the World Ocean. *Deep Sea Res.* 56, 295–304. doi: 10.1016/j.dsr.2008.09.010

Sepulveda, H. H., Queffeulou, P., and Ardhuin, F. (2015). Assessment of SARAL/AltiKa wave height measurements relative to buoy, Jason-2, and Cryosat-2 data. *Mar. Geod.* 38, 449–465. doi: 10.1080/01490419.2014.1000470

Shakespeare, C. J., and Taylor, J. (2013). A generalized mathematical model of geostrophic adjustment and frontogenesis: uniform potential vorticity. *J. Fluid Mech.* 736, 366–413. doi: 10.1017/jfm.2013.526

Shearman, K. R., and Lentz, S. J. (2010). Long-term sea surface temperature variability along the U.S. East Coast. *J. Phys. Oceanogr.* 40, 1004–1017. doi: 10.1175/2009JPO4300.1

Shimura, T., Mori, N., Takemi, T., and Mizuta, R. (2017). Long-term impacts of ocean wave-dependent roughness on global climate systems. *J. Geophys. Res. Oceans* 122, 1995–2011. doi: 10.1002/2016JC012621

Siedlecki, S. A., Banas, N. S., Davis, K. A., Giddings, S., Hickey, B. M., MacCready, P., et al. (2015). Seasonal and interannual oxygen variability on the Washington and Oregon continental shelves. *J. Geophys. Res. Oceans* 120, 608–633. doi: 10.1002/2014JC010254

Siedlecki, S. A., Kaplan, I. C., Hermann, A. J., Nguyen, T. T., Bond, N. A., Newton, J. A., et al. (2016). Experiments with seasonal forecasts of ocean conditions for the northern region of the California Current upwelling system. *Sci. Rep.* 6:27203. doi: 10.1038/srep27203

Simmons, H. L., and Alford, M. H. (2012). Simulating the long-range swell of internal waves generated by ocean storms. *Oceanography* 25, 30–41. doi: 10.5670/oceanog.2012.39

Simons, R. D., Siegel, D. A., and Brown, K. S. (2013). Model sensitivity and robustness in the estimation of larval transport: a study of particle tracking parameters. *J. Mar. Syst.* 119–120, 19–29. doi: 10.1016/j.jmarsys.2013.03.004

Simpson, J. E. (1994). *Sea Breeze and Local Winds*. Cambridge, UK: Cambridge University Press.

Small, R., Xie, S., O'Neill, L., Seo, H., Song, Q., Cornillon, P., et al. (2008). Air–sea interaction over ocean fronts and eddies. *Dyn. Atmos. Oceans* 45, 274–319. doi: 10.1016/j.dynatmoce.2008.01.001

Smyth, W., Moum, J., Li, L., and Thorpe, S. (2013). Diurnal shear instability, the descent of the surface shear layer, and the deep cycle of equatorial turbulence. *J. Phys. Oceanogr.* 43, 2432–2455. doi: 10.1175/JPO-D-13-089.1

Soloviev, Y. P., and Kudryavtsev, V. (2010). Wind-speed undulations over swell: field experiment and interpretation. *Bound. Layer Meteorol.* 136, 341–363. doi: 10.1007/s10546-010-9506-z

Squire, V. A. (2018). A fresh look at how ocean waves and sea ice interact. *Phil. Trans. R. Soc. A* 376:20170342. doi: 10.1098/rsta.2017.0342

Srinivasan, K., McWilliams, J. C., Renault, L., Hristova, H. G., Molemaker, J., and Kessler, W. S. (2017). Topographic and mixed layer submesoscale currents in the near-surface southwestern tropical Pacific. *J. Phys. Oceanogr.* 47, 1221–1242. doi: 10.1175/JPO-D-16-0216.1

Stammer, D., Balmaseda, M., Heimbach, P., Köhl, A., and Weaver, A. (2016). Ocean data assimilation in support of climate applications: status and perspectives. *Annu. Rev. Mar. Sci.* 8, 491–518. doi: 10.1146/annurev-marine-122414-034113

Steele, M., Zhang, J., Rothrock, D., and Stern, H. (1997). The force balance of sea ice in a numerical model of the Arctic Ocean. *J. Geophys. Res. Oceans* 102, 21061–21079. doi: 10.1029/97JC01454

Stoffelen, A., Aaboe, S., Calvet, J.-C., Cotton, J., De Chiara, G., Saldana, J., et al. (2017). Scientific developments and the EPS-SG scatterometer. *IEEE J. Select. Top. Appl. Earth Observ. Rem. Sens.* 10, 2086–2097. doi: 10.1109/JSTARS.2017.2696424

Stopa, J., Ardhuin, F., Thomson, J., Smith, M. M., Kohout, A., Doble, M., et al. (2018). Wave attenuation through an Arctic marginal ice zone on 12 October 2015. 1. Measurement of wave spectra and ice features from sentinel 1A. *J. Geophys. Res. Oceans* 123, 3619–3634. doi: 10.1029/2018JC013791

Stroeve, J., and Notz, D. (2018). Changing state of Arctic sea ice across all seasons. *Environ. Res. Lett.* 13:103001. doi: 10.1088/1748-9326/aade56

Strong, C., and Rigor, I. G. (2013). Arctic marginal ice zone trending wider in summer and narrower in winter. *Geophys. Res. Lett.* 40, 4864–4868. doi: 10.1002/grl.50928

Suanda, S. H., Kumar, N., Miller, A. J., Di Lorenzo, E., Haas, K., Cai, D., et al. (2016). Wind relaxation and a coastal buoyant plume north of Pt. Conception, CA: observations, simulations, and scalings. *J. Geophys. Res. Oceans* 121, 7455–7475. doi: 10.1002/2016JC011919

Sudre, J., Maes, C., and Garçon, V. (2013). On the global estimates of geostrophic and Ekman surface currents. *Limnol. Oceanogr. Fluids Environ.* 3, 1–20. doi: 10.1215/21573689-2071927

Sullivan, P. P., and McWilliams, J. C. (2018). Frontogenesis and frontal arrest of a dense filament in the oceanic surface boundary layer. *J. Fluid Mech.* 837, 341–380. doi: 10.1017/jfm.2017.833

Sumata, H., Kwok, R., Gerdes, R., Kauker, F., and Karcher, M. (2015). Uncertainty of Arctic summer ice drift assessed by high-resolution SAR data. *J. Geophys. Res. Oceans* 120, 5285–5301. doi: 10.1002/2015JC010810

Sutherland, P., and Dumont, D. (2018). Marginal ice zone thickness and extent due to wave radiation stress. *J. Phys. Oceanogr.* 48, 1885–1901. doi: 10.1175/JPO-D-17-0167.1

Suzuki, N., and Fox-Kemper, B. (2016). Understanding stokes forces in the wave-averaged equations. *J. Geophys. Res.* 121, 3579–3596. doi: 10.1002/2015JC011566

Suzuki, N., Fox-Kemper, B., Hamlington, P. E., and Van Roekel, L. P. (2016). Surface waves affect frontogenesis. *J. Geophys. Res. Oceans* 121, 3597–3624. doi: 10.1002/2015JC011563

Swenson, M. S., and Hansen, D. V. (1999). Tropical Pacific Ocean mixed layer heat budget: the Pacific cold tongue. *J. Phys. Oceanogr.* 29, 69–81. doi: 10.1175/1520-0485(1999)029<0069:TPOMLH>2.0.CO;2

Teinturier, S., Stegner, A., Didelle, H., and Viboud, S. (2010). Small-scale instabilities of an island wake flow in a rotating shallow-water layer. *Dyn. Atmos. Oceans* 49, 1–24. doi: 10.1016/j.dynatmoce.2008.10.006

Teixeira, M., and Belcher, S. (2002). On the distortion of turbulence by a progressive surface wave. *J. Fluid Mech.* 458, 229–267. doi: 10.1017/S0022112002007838

Terrill, E., Otero, M., Hazard, L., Conlee, D., Harlan, J., Kohut, J., et al. (2006). "Data management and real-time distribution in the HF-radar national network," in *OCEANS 2006* (Boston, MA: IEEE), 1–6.

Thomas, L. N., and Lee, C. M. (2005). Intensification of ocean fronts by down-front winds. *J. Phys. Oceanogr.* 35, 1086–1102. doi: 10.1175/JPO2737.1

Thomas, L. N., Taylor, J. R., D'Asaro, E. A., Lee, C. M., Klymak, J. M., and Shcherbina, A. (2016). Symmetric instability, inertial oscillations, and turbulence at the Gulf Stream front. *J. Phys. Oceanogr.* 46, 197–217. doi: 10.1175/JPO-D-15-0008.1

Thomas, L. N., Taylor, J. R., Ferrari, R., and Joyce, T. M. (2013). Symmetric instability in the Gulf Stream. *Deep Sea Res.* 91, 96–110. doi: 10.1016/j.dsr2.2013.02.025

Thompson, A. F., Lazar, A., Buckingham, C., Naveira Garabato, A. C., Damerell, G. M., and Heywood, K. J. (2016). Open-ocean submesoscale motions: a full seasonal cycle of mixed layer instabilities from gliders. *J. Phys. Oceanogr.* 46, 1285–1307. doi: 10.1175/JPO-D-15-0170.1

Thomson, J., R, H. A., Zippel, S., Rusch, C., and Geyer, W. (2014). Wave breaking turbulence at the offshore front of the Columbia River Plume. *Geophys. Res. Lett.* 41, 8987–8993. doi: 10.1002/2014GL062274

Tozuka, T., Ohishi, S., and Cronin, M. F. (2018). A metric for surface heat flux effect on horizontal sea surface temperature gradients. *Clim. Dyn.* 51, 547–561. doi: 10.1007/s00382-017-3940-2

Tsamados, M., Feltham, D., Petty, A., Schroeder, D., and Flocco, D. (2015). Processes controlling surface, bottom and lateral melt of Arctic sea ice in a state of the art sea ice model. *Phil. Trans. R. Soc. A* 373:20140167. doi: 10.1098/rsta.2014.0167

Tschudi, M., Fowler, C., Maslanik, J., Stewart, J., and Meier, W. (2016). *Polar Pathfinder Daily 25 km EASE-Grid Sea Ice Motion Vectors, Version 3*. Boulder, CO: National Snow and Ice Data Center Distributed Active Archive Center.

Unwin, M., Gao, S., De Vos Van Steenwijk, R., Jales, P., Maqsood, M., Gommenginger, C., et al. (2013). Development of low-cost spaceborne multi-frequency GNSS receiver for navigation and GNSS remote sensing. *Int. J. Space Sci. Eng.* 1, 20–50. doi: 10.1504/IJSPACESE.2013.051757

Van Sebille, E., Griffies, S. M., Abernathey, R., Adams, T. P., Berloff, P., Biastoch, A., et al. (2017). Lagrangian ocean analysis: fundamentals and practices. *Ocean Modell.* 121, 49–75. doi: 10.1016/j.ocemod.2017.11.008

Van Sebille, E., Wilcox, C., Lebreton, L., Maximenko, N., Hardesty, B. D., Van Franeker, J. A., et al. (2015). A global inventory of small floating plastic debris. *Environ. Res. Lett.* 10:124006. doi: 10.1088/1748-9326/10/12/124006

Vandemark, D., Edson, J. B., and Chapron, B. (1997). Altimeter estimation of sea surface wind stress for light to moderate winds. *J. Atmos. Ocean. Technol.* 14, 716–722. doi: 10.1175/1520-0426(1997)014<0716:AEOSSW>2.0.CO;2

Veeramony, J., Orzech, M. D., Edwards, K. L., Gilligan, M., Choi, J., Terrill, E., et al. (2014). Navy nearshore ocean prediction systems. *Oceanography* 27, 80–91. doi: 10.5670/oceanog.2014.70

Veras Guimarães, P., Ardhuin, F., Sutherland, P., Accensi, M., Hamon, M., Pérignon, Y., et al. (2018). A surface kinematics buoy (skib) for wave-current interactions studies. *Ocean Sci. Discuss.* 2018, 1–20. doi: 10.5194/os-2018-45

Verdy, A., and Mazloff, M. (2017). A data assimilating model for estimating Southern Ocean biogeochemistry. *J. Geophys. Res. Oceans* 122, 6968–6988. doi: 10.1002/2016JC012650

Vigan, X., Provost, C., and Podesta, G. (2000). Sea surface velocities from sea surface temperature image sequences: 2. Application to the Brazil-Malvinas Confluence area. *J. Geophys. Res. Oceans* 105, 19515–19534. doi: 10.1029/2000JC900028

Villas Bôas, A., Sato, O., Chaigneau, A., and Castelão, G. (2015). The signature of mesoscale eddies on the air-sea turbulent heat fluxes in the South Atlantic Ocean. *Geophys. Res. Lett.* 42, 1856–1862. doi: 10.1002/2015GL063105

Villas Bôas, A. B., Gille, S. T., Mazloff, M. R., and Cornuelle, B. D. (2017). Characterization of the deep water surface wave variability in the California Current region. *J. Geophys. Res. C Oceans* 122, 8753–8769. doi: 10.1002/2017JC013280

Walter, R. K., Armenta, K. J., Shearer, B., Robbins, I., and Steinbeck, J. (2018). Coastal upwelling seasonality and variability of temperature and chlorophyll in a small coastal embayment. *Cont. Shelf Res.* 154, 9–18. doi: 10.1016/j.csr.2018.01.002

Walter, R. K., Stastna, M., Woodson, C. B., and Monismith, S. G. (2016). Observations of nonlinear internal waves at a persistent coastal upwelling front. *Cont. Shelf Res.* 117, 100–117. doi: 10.1016/j.csr.2016.02.007

Wanninkhof, R. (2014). Relationship between wind speed and gas exchange over the ocean revisited. *Limnol. Oceanogr. Methods* 12, 351–362. doi: 10.4319/lom.2014.12.351

Warren, M., Quartly, G. D., Shutler, J., Miller, P. I., and Yoshikawa, Y. (2016). Estimation of ocean surface currents from maximum cross correlation applied to GOCI geostationary satellite remote sensing data over the Tsushima (Korea) Straits. *J. Geophys. Res. Oceans* 121, 6993–7009. doi: 10.1002/2016JC011814

Washburn, L., Fewings, M., Melton, C., and Gotschalk, C. (2011). The propagating response of coastal circulation due to wind relaxations along the central California coast. *J. Geophys. Res.* 116:C12028. doi: 10.1029/2011JC007502

Watson, A. J., Schuster, U., Bakker, D. C., Bates, N. R., Corbière, A., Gonzáez-Dávila, M., et al. (2009). Tracking the variable North Atlantic sink for atmospheric CO2. *Science* 326, 1391–1393. doi: 10.1126/science.1177394

Weisberg, R. H., and Weingartner, T. J. (1988). Instability waves in the equatorial Atlantic Ocean. *J. Phys. Oceanogr.* 18, 1641–1657. doi: 10.1175/1520-0485(1988)018<1641:IWITEA>2.0.CO;2

Weissman, D. E., King, D., and Thompson, T. W. (1979). Relationship between hurricanes surface winds and L-band radar backscatter from the sea surface. *J. Appl. Meteorol.* 18, 1023–1034. doi: 10.1175/1520-0450(1979)018<1023:RBHSWA>2.0.CO;2

Weller, R. A., and Davis, R. E. (1980). A vector measuring current meter. *Deep Sea Res.* 27, 565–581. doi: 10.1016/0198-0149(80)90041-2

Wenegrat, J. O., and McPhaden, M. J. (2015). Dynamics of the surface layer diurnal cycle in the equatorial atlantic ocean (0°, 23° w). *J. Geophys. Res. Oceans* 120, 563–581. doi: 10.1002/2014JC010504

Wentz, F. J., Ricciardulli, L., Rodriguez, E., Stiles, B. W., Bourassa, M. A., Long, D. G., et al. (2017). Evaluating and extending the ocean wind climate data record. *IEEE J. Select. Top. Appl. Earth Observ. Rem. Sens.* 10, 2165–2185. doi: 10.1109/JSTARS.2016.2643641

Winant, C. D., Dorman, C. E., Friehe, C. A., and Beardsley, R. C. (1988). The marine layer off Northern California: an example of supercritical channel flow. *J. Atmos. Sci.* 45, 3588–3605. doi: 10.1175/1520-0469(1988)045<3588:TMLONC>2.0.CO;2

Wishner, K. F., Outram, D. M., and Ullman, D. S. (2006). Zooplankton distributions and transport across the northeastern tidal front of Georges Bank. *Deep Sea Res.* 53, 2570–2596. doi: 10.1016/j.dsr2.2006.06.003

Wong, P. P., Losada, I. J., Gattuso, J. P., Hinkel, J., Khattabi, A., McInnes, K. L., et al. (2014). "Coastal systems and low-lying areas," in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Chapter 5 (Cambridge; New York, NY: Cambridge University Press), 361–409.

Woodson, C. B., Washburn, L., Barth, J. A., Hoover, D. J., Kirincich, A. R., McManus, M. A., et al. (2009). Northern Monterey Bay upwelling shadow front: observations of a coastally and surface-trapped buoyant plume. *J. Geophys. Res. Oceans* 114. doi: 10.1029/2009JC005623

Woolf, D. K., Land, P. E., Shutler, J. D., Goddijn-Murphy, L. M., and Donlon, C. J. (2016). On the calculation of air-sea fluxes of CO2 in the presence of temperature and salinity gradients. *J. Geophys. Res.* 121, 1229–1248. doi: 10.1002/2015JC011427

Xie, S.-P., Ishiwatari, M., Hashizume, H., and Takeuchi, K. (1998). Coupled ocean-atmospheric waves on the equatorial front. *Geophys. Res. Lett.* 25, 3863–3866. doi: 10.1029/1998GL900014

Xie, S. P., Liu, W. T., Liu, Q., and Nonaka, M. (2001). Far-reaching effects of the Hawaiian Islands on the Pacific Ocean-atmosphere system. *Science* 292, 2057–2060. doi: 10.1126/science.1059781

Yurovsky, Y., Kudryavtsev, V., Grodsky, S., and Chapron, B. (2018). Low-frequency sea surface radar Doppler echo. *Rem. Sens.* 10:870. doi: 10.3390/rs10060870

Zavorotny, V. U., Gleason, S., Cardellach, E., and Camps, A. (2014). Tutorial on remote sensing using GNSS bistatic radar of opportunity. *IEEE Geosci. Rem. Sens. Mag.* 2, 8–45. doi: 10.1109/MGRS.2014.2374220

Zhang, B., Perrie, W., and He, Y. (2011). Wind speed retrieval from RADARSAT-2 quad-polarization images using a new polarization ratio model. *J. Geophys. Res. Oceans* 116:C08008. doi: 10.1029/2010JC006522

Zhang, W. G., and Gawarkiewicz, G. G. (2015). Dynamics of the direct intrusion of Gulf Stream ring water onto the Mid-Atlantic Bight shelf. *Geophys. Res. Lett.* 42, 7687–7695. doi: 10.1002/2015GL065530

Zippel, S., and Thomson, J. (2017). Surface wave breaking over sheared currents: observations from the mouth of the Columbia River. *J. Geophys. Res. Oceans* 122, 3311–3328. doi: 10.1002/2016JC012498

Zuidema, P., Chang, P., Medeiros, B., Kirtman, B. P., Mechoso, R., Schneider, E. K., et al. (2016). Challenges and prospects for reducing coupled climate model SST biases in the eastern tropical Atlantic and Pacific oceans: the US CLIVAR Eastern Tropical Oceans Synthesis Working Group. *Bull. Am. Meteorol. Soc.* 97, 2305–2328. doi: 10.1175/BAMS-D-15-00274.1

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The Winds and Currents Mission Concept

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The Winds and Currents Mission (WaCM) is a proposed approach to meet the need identified by the NRC Decadal Survey for the simultaneous measurements of ocean vector winds and currents. WaCM features a Ka-band pencil-beam Doppler scatterometer able to map ocean winds and currents globally. We review the principles behind the WaCM measurement and the requirements driving the mission. We then present an overview of the WaCM observatory and tie its capabilities to other OceanObs reviews and measurement approaches.

Keywords: surface currents, surface winds, Doppler, scatterometer, air-sea interaction, sea ice, relative vorticity

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1. INTRODUCTION

Air-sea interaction is a critical component of the Earth's weather and climate systems and also plays an important role in ocean biology. Ocean surface winds couple the ocean and atmosphere, driving ocean circulation, and influencing fluxes across the air-sea interface. Ocean surface currents determine horizontal and vertical transport of heat, nutrients, and gases near the ocean surface, and also modulate the atmospheric wind forcing. Over the polar regions, both winds and currents play determining roles in the motion of sea ice and fresh water released by melting ice sheets. Since they form a tightly coupled dynamic system, surface winds and currents must be observed together at appropriate space and time scales. The joint measurement of these two essential climate variables (ECVs) has been recommended as a targeted observable for the next decade of NASA spaceborne observations by the 2018 Decadal Review (National Academies of Sciences, Engineering, and Medicine, 2018). Here, we present a conceptual measurement approach for a Winds and Currents Mission (WaCM) capable of meeting the observational goals outlined by the Decadal Review.

Radar altimeters have revolutionized monitoring large-scale *geostrophic* ocean currents (e.g., Stammer and Cazenave, 2017), but limited coverage by the altimetry constellation restricts the resolution to spatial scales $\sim$ 200 km and temporal scales of about a month. The ocean contains significant variability at smaller scales and the NASA/CNES SWOT mission (Durand et al., 2010) will soon provide high spatial resolution measurements of small mesoscale features. SWOT will provide significant insights into small scale Sea Surface Height (SSH) variability, but its limited swath restricts its ability for forming temporal averages of spatial derivatives to compute geostrophic velocity and double derivatives to compute vorticity (Chelton et al., 2018) (see **Figure 1**).

Even if geostrophic currents were determined precisely, surface currents contain additional contributions from Ekman (Lagerloef et al., 1999) and inertial currents (Alford et al., 2014) (both related to winds), tidal currents, and near surface currents driven by wind and wave induced

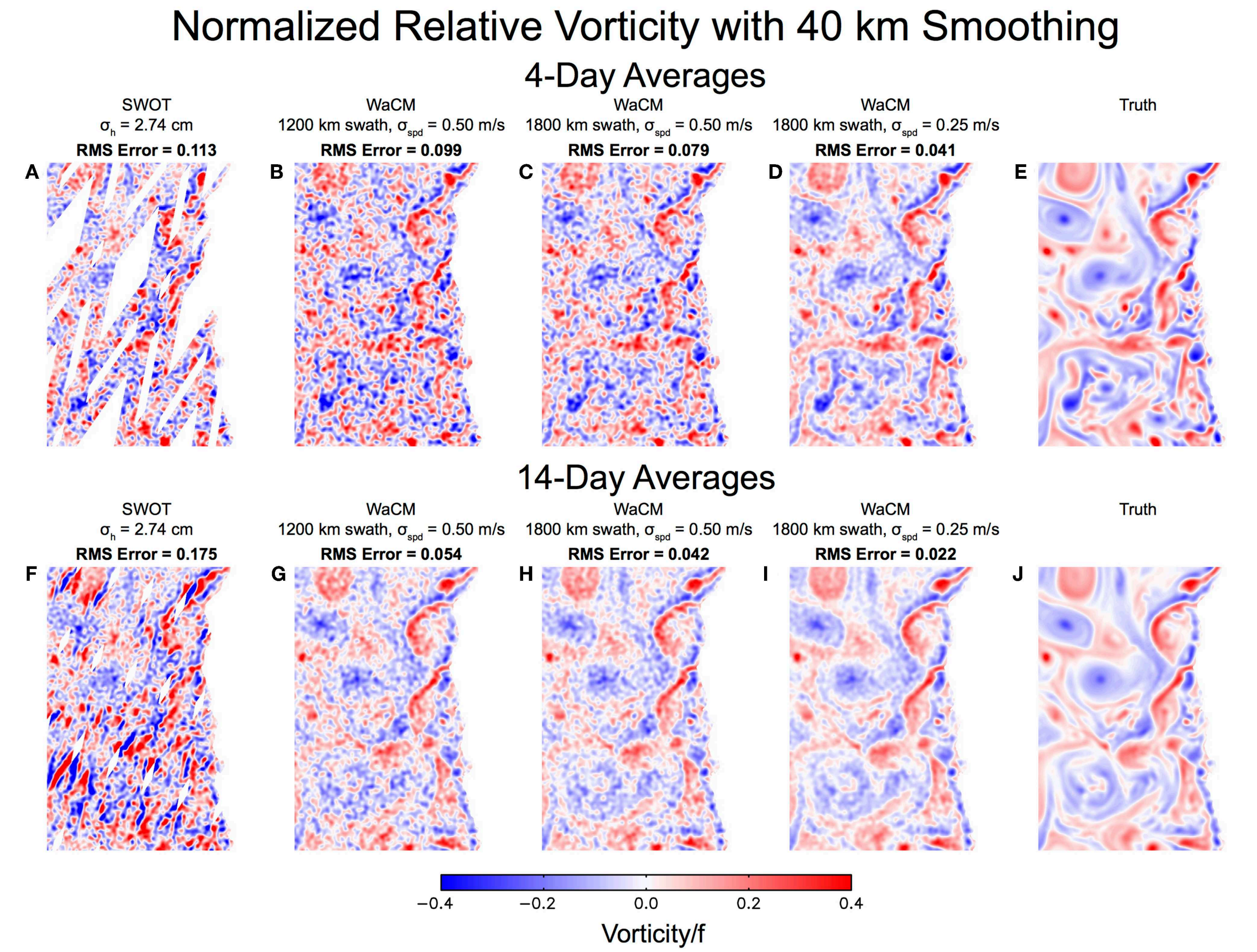

FIGURE 1 | Simulated relative vorticity fields in the California Current System averaged for 4 **(E)** and 14 **(J)** days. On the left **(A,F)** are the same average fields sampled by the NASA/CNES SWOT mission, showing the problems with small swath coverage. The same fields sampled by WaCM assuming an 1,800 km swath and 50 cm/s **(C,H)** or 40 cm/s speed noise at 5 km sampling. The impact of swath width is shown in **B,G**, to be compared with **C,H**, where only a 1,200 km swath was used for sampling. **D,I** show the impact of reducing measurement noise from 50 cm/s to 25 cm/s. These results are taken from Chelton et al. (2018).

instabilities (McWilliams, 2016). Although there have been efforts to compliment geostrophic currents by adding a wind driven Ekman component (Bonjean and Lagerloef, 2002), probing smaller scales requires coincident data and the inclusion of additional physics beyond a simple Ekman layer. Surface current divergence, an indicator of vertical circulation and mixing, may be resolvable by a total current WaCM sensor (Chelton et al., 2018), but cannot be computed from the geostrophic currents estimated from SWOT data. It is therefore necessary to develop sensors that are sensitive directly to the total surface current velocity, not just the geostrophic current.

Radar scatterometers, such as NASA's QuikSCAT or EUMETSAT's ASCAT, have demonstrated the capability to retrieve stress-equivalent winds (de Kloe et al., 2017) globally. Although the ASCAT constellation is operational, and complemented in by scatterometers launched by India (ScatSat-1) and China (HY2A, HY2B, CFOSAT), the sampling currently available (concentrated at ~9a.m./9p.m. or ~6a.m./6p.m., with systematic daily gaps in the tropics and mid-latitudes, ∼25 km spatial resolution) is not sufficient to provide measurements of global winds/stress and wind/stress derivatives at appropriate space-time sampling, which, as we discuss below require both wide-swath coverage and high spatial resolution. To achieve these two requirements, the WaCM mission will collect both winds and currents from the same platform.

For WaCM, we propose to use Doppler scatterometry, described in section 2, to obtain simultaneous measurements of total ocean surface currents and winds. Meeting appropriate sampling and performance requirements, reviewed in section 3, is key for the viability of WaCM. How these requirements are met by a Doppler scatterometer system using current technology is reviewed in section 4. Finally, section 5 ties WaCM to the science goals and measurement concepts outlined by other contributions to 2019 OceanObs survey.

2. DOPPLER SCATTEROMETRY

Our science goals require an instrument that can provide simultaneous measurements of winds and ocean surface currents: we examine the state of retrieving these from space.

2.1. Measuring Winds

The estimation of ocean vector winds through the radar cross section measured by scatterometers, such as NASA's Ku-band QuikSCAT and ESA's C-band ASCAT, is a mature technology. Over the next decade both EUMETSAT and ISRO will likely continue to operate scatterometers, and China's scatterometer data products may be validated for science use and become publicly available. These sensors will complement the wind and current measurements of WaCM.

One of the key issues in air-sea interaction is the measurement of both vector winds and currents at ocean fronts (Chelton et al., 2004), which can be quite sharp as spatial scales decrease (McWilliams, 2016). Pencil-beam scatterometers can provide adequate wind directions at scales of about 25 km, although wind speeds at higher resolution can be estimated using super-resolution techniques (Plagge et al., 2009). Improved processing of ASCAT data (Vogelzang and Stoffelen, 2016), can also improve the spatial posting, although the Spatial Response Function (SRF) (Lindsley et al., 2016) limits spectral resolution; this may be improved in the future SCA EUMETSAT instrument (Lin et al., 2017). Although finer resolution can be achieved with traditional scatterometers, it comes at the cost of higher noise. Since the wind stress curl is essential to understanding wind-current interactions, we seek a system that can improve the spatial resolution of existing scatterometers at low-noise performance. This improvement can be accomplished by using Ka-band ($\sim$ 35 GHz) radars, which will reduce the ground azimuth footprint by a factor of $\sim$3 relative to Ku-band, for a given antenna size. The azimuth resolution can be further improved by increasing the antenna size. Although there have been no spaceborne Ka-band scatterometer systems, the sensitivity of Ka-band to wind speed and direction has been established by radar measurements from towers (Yurovsky et al., 2016) and airplanes (Masuko et al., 1986; Rodriguez et al., 2018). All field measurements are consistent in showing Ka-band sensitivities to both wind speed and direction that are at least as good as are observed at Ku-band.

2.2. Measuring Surface Currents

The direct measurement of ocean surface velocities is achieved through measurements of the Doppler shift of the radar returns, which is proportional to the component of the ocean surface velocity along the line of sight. This technique was first demonstrated by airborne radars using along-track interferometry (ATI) (Goldstein et al., 1989). The surface current along the line of sight can be obtained, given the wind speed and direction, by removing the known phase speed of the resonant Bragg waves and contamination from brightness variations along surface gravity waves. Chapron et al. (2005) realized that some surface current information could be obtained by using the Doppler anomalies in a single-antenna radar system, and they have demonstrated retrievals over multiple ocean targets (Johannessen et al., 2008; Rouault et al., 2010). To go from radial velocity to vector velocity measurements, one needs to observe the radial velocity along different azimuth directions. Recently, several teams (Bao et al., 2015; Rodriguez et al., 2018) have proposed using a pencil-beam approach, such as the one on QuikSCAT, to obtain surface velocity estimates, and Rodriguez et al. (2018) have demonstrated the principle using airborne data.

The last decade has also seen the maturing of the theoretical basis for the geophysical algorithms required to separate the current from the Bragg wave and large-scale wave motions (e.g., Johannessen et al., 2008). Although helpful in guiding the understanding of the underlying physics, theory is not yet at the stage where it can be used to remove the contamination due to surface waves. For the moment, an approach based on a geophysical model function (GMF) that parametrizes the surface wave contamination as a function of wind speed and direction has been proposed and demonstrated using both airborne (Rodriguez et al., 2018) and tower data (Yurovsky et al., 2018). Although successful in removing much of the surface wave contamination, an empirical correlation approach can remove true surface current components, such as Stokes drift, that are directly correlated with the wind speed and direction and which may also be of geophysical interest.

Another issue with Doppler measurements is that they are sensitive to velocities at the actual ocean surface, and not to the more commonly used velocities at depths of order 10 m: current shear with depth must be accounted for when relating the two (Morey et al., 2018). Recently, Clarke and Van Gorder (2018) have examined empirically the contribution of Stokes drift and concluded that it is mainly driven by short waves generated by the local wind, so that the Stokes drift can be estimated from the wind stress measured by the scatterometer, highlighting again the need for simultaneous wind and current measurements. Both the GMF and current shear issue will need to be addressed in greater detail, both experimentally and theoretically, to mature the Doppler current concept to its full potential.

Note that the Doppler velocity concept also applies to tracking of sea ice, where greater radar brightness and no wave motion results in a more accurate measurement of velocity than over the ocean.

3. RESOLUTION AND ACCURACY REQUIREMENTS

The mission sampling requirements are not set merely by the accuracy and temporal resolution of the surface wind and current velocities. Since the curl of the wind stress and surface current are both important in air-sea interaction, one must consider the requirements for sampling velocity field derivatives, as well the fields themselves (Bourassa and McBeth-Ford, 2010). It is well-known that the derivative operator amplifies the errors of the measured variable.

3.1. Spatial Coverage

Global coverage, including the polar ocean, requires high inclination orbits. Most scatterometer missions are sun-synchronous (orbit inclination ∼98°) which is sufficient to meet our goals, provided sun-synchronous signals, such as tides, can be removed reliably. While the elevation changes due to tides are well-known in the deep ocean (Stammer and Cazenave, 2017), their surface velocity expression has been less validated. Other high-inclination non-sun-synchronous orbits in the range between 82° and 98°, which may have better diurnal and tidal sampling, would also meet our observation requirements.

3.2. Space-Time Sampling

Temporal sampling of surface currents drives the mission design. In the tropics, temporal scales may be adequately sampled by observations separated by a few days. Elsewhere, small mesoscale features (30 to 100 km) not resolved by the altimeter constellation have lifetimes that range between 1 day and less than 1 week. To resolve synoptic surface wind variability and the sub-inertial ocean response or weak-wind or deep-mixed-layer conditions, one must consider time scales associated with the atmosphere-ocean coupling on the order of days to a week at scales of 100–200 km. For WaCM, simultaneous winds and surface currents will be at a frequency of 1–2 times per day (mitigating aliasing from tides and inertial motions), but temporal averages over several days are required to resolve relative vorticity features for the smallest scales.

Appropriate temporal sampling of coincident winds and currents is a major observational requirement (Wentz et al., 2017). Simultaneous observations are desired to study wind and current coupling, and the simultaneous measurements collected by WaCM will avoid temporal sampling. WaCM winds could complement, and be complemented by ongoing operational platforms, such as EUMETSAT's ASCAT, ISRO's SCATSAT-1, China's HY series, CFOSAT and WindRad.

An additional space-time coverage issue is the ability to gain synoptic views of the ocean circulation so that derivatives (such as vorticity) can be calculated and an assessment can be made of the temporal evolution of the two dimensional field (Chelton et al., 2018). **Figure 1** compares simulated temporally averaged relative vorticity fields from the 120 km-swath NASA SWOT mission and those from the wide-swath WaCM scatterometer described below. Even though the instantaneous SWOT data have smaller random noise, the distortion in the time-averaged fields due to measurement gaps and the rapid evolution of small-scale features dominates the relative vorticity synoptic map errors. This is the case for short (4-day) averages and is even more of an issue when the temporal averages are conducted over 2 weeks.

Care must also be taken that wind-driven inertial motions not be aliased into the low-frequency signal. The period of inertial motions varies with latitude. In the tropics, the inertial period is long (e.g., 69 h at 10° latitude) and should not present a major sampling problem. However, the inertial period becomes shorter than one day at latitudes higher than 30° and appropriate sampling requires several observations per day. Current wide-swath radar scatterometers can achieve this sampling up to mid-latitudes, but it is possible that some of the inertial signals might alias at higher latitudes. At these latitudes, the use of models provides a means for removing the inertial motion contributions. To demonstrate the feasibility of this approach, we have examined the coherence of *in situ* inertial current measurements with an internal-wave admitting global ocean simulation (Rocha et al., 2016) driven by ECMWF atmospheric analysis and found there is significant coherence between simulated and observed inertial currents. This suggests that the effects of aliasing of near-inertial currents could be reduced by modeling and removing the inertial signal or by fitting for it, given sufficient duration and known oscillation periods. This is an area of active study.

3.3. Spatial Resolution

The spatial resolution of the measurements is driven by: avoiding contamination due to land and rain; the need to compute spatial derivatives (e.g., wind stress curl); the desire to resolve smaller features (wind and current) that may appear at higher latitudes or in coastal regions; and, consistency between wind and current estimates. High resolution is also required in the polar oceans or in the coastal regions to discriminate between land/ice and water. Based on previous scatterometer experience near land and rain, these requirements imply the need for spatial resolution of about 5 km, or a factor of ∼5 improvement over the existing capabilities. Although the scatterometer signal for both Ku and Ka-band scatterometers is strongly attenuated by rain, we expect the significantly smaller resolution cell of WaCM will help in rejecting rain cells and cover the areas around them, improving on Ku-band scatterometer rain contamination. We also expect that the joint backscatter and Doppler signatures will allow for the simultaneous estimation of winds and rain, building on Draper and Long (2004).

3.4. Measurement Accuracy

The accuracy requirements are driven by the atmosphere-ocean coupling target. Using classical Ekman and bulk mixed-layer models to characterize the ageostrophic surface current component, accuracy requirements on stress can be derived. Experience with existing satellite scatterometer systems indicates that a precision of 0.02 N m^{-2} (equivalent to about 1.5 m/s wind speed) for surface stress is adequate to characterize the local wind field (Bourassa et al., 2019).

Computing the surface current vorticity and divergence places the most stringent requirements on the surface current accuracies. Chelton et al. (2018) have examined the resolutions that can be achieved for the velocity and vorticity fields in the California Current System (CCS) as a function of current component noise, temporal averaging, and swath width. They conclude that an 1,800 km swath and speed error of 50 cm/s for 5 km samples can resolve wavelength scales 45 km in the velocity and 70 km in the vorticity, assuming averaging over 4 days. Reducing the speed error to 25 cm/s further improves these resolution capabilities to about 20 and 45 km, respectively. As shown by Chelton et al. (2018; Appendix B), the feature diameter corresponds to about 1/2 of the resolved wavelengths, so one could resolve eddies whose diameter is 10 km (velocity) or 22.5 km (vorticity), which starts to probe ocean submesoscales. **Figure 1** illustrates the resolution capabilities for different speed errors and swath widths, showing that the small mesoscale field will be appropriately sampled by a Doppler scatterometer system that can achieve an 1,800 km swath and speed accuracies between 25 and 50 cm/s sampled at 5 km.

4. OBSERVING SYSTEM

The measurement requirements lead to a sensor that has the following characteristics: ability to measure currents and winds simultaneously; large swath ($\sim 1,800$ km); high spatial resolution (< 5 km); continuous spatial coverage without significant gaps; current speed errors better than 50 cm/s. Rodriguez (2018) has proposed a design approach for WaCM that meets these requirements. Some highlights include:

- A pencil-beam scanning antenna architecture with a $\sim 56^\circ$ radar incidence angle. For orbits in the 700–800 km altitude range (i.e., OSCAT to QuikSCAT orbits), swaths between 1,700 and 1,900 km will be achieved, consistent with the spatial coverage and temporal sampling above and the recommendations in Chelton et al. (2018).
- A Ka-band, vertically polarized, Doppler scatterometer with a long ($\sim$ 5 m) skinny ($\sim$ 0.3 m) rotating antenna. The antenna length, which is substantially longer and narrower than the one in past scatterometers, has multiple benefits: (a) The azimuth resolution will be $<$ 3 km (8 times better than QuikSCAT), enabling the computation of current velocity derivatives with sufficient accuracy (Chelton et al., 2018) and leading to significant improvements in resolution that will be of importance at the ice edge and at the coasts. (b) Increases in signal-to-noise ratios, leading to improvements in random error performance that will meet or exceed the accuracy requirements in section 3 (see **Figure 2**). The narrow antenna dimension produces a large footprint in the range direction, so that continuous coverage is achieved at lower antenna rotation speeds than for circular antennas.
- A pulse repetition frequency (PRF) that varies with azimuth angle, which optimizes the pulse separation and energy per pulse, resulting in the surface velocity errors in **Figure 2**. The variable PRF significantly increases the imaged range ambiguity-free swath, and results in continuous coverage without need for interpolation. This in contrast with high-PRF systems (e.g., Ardhuin et al., 2018), where a limited range swath requires filling in voids using an interpolation scheme.

The WaCM errors quoted above assume the availability of off-the-shelf components with known performance for most of the instrument. Although not standard, the antenna assumed here is similar to a light, deployable reflectarray antenna developed by NASA's JPL for the SWOT mission (Hodges and Zawadzki, 2012), whose modification for WaCM is currently under study. One of the mission cost drivers is the radar RF source, since power drives the size and complexity of the spacecraft, so, in lieu of a detailed cost estimate at present, we show in **Figure 2** the performance for several options spanning possible RF sources, and note that the threshold measurement objectives are met even for the lowest power solution, although additional power will enhance the science returns significantly.

5. SCIENCE OBJECTIVES AND RELATIONSHIP TO OTHER OCEANOBS REVIEWS

WaCM would offer the first global data set of simultaneous measurements of ocean surface currents, winds, and sea ice sampled nearly twice per day with 5 km footprint. These capabilities are expected to make contributions in three broad areas:

- **Ocean-Atmosphere Interactions**: By measuring total surface currents, WaCM will provide a unique capability to monitor the non-geostrophic equatorial oceans, which play a key role in ocean heat uptake and carbon outgassing and are key in understanding the ocean's meridional heat transport (Villas Boas et al., 2019). At higher latitudes, WaCM would contribute to an improved understanding of wind- and current-driven ocean upwelling mechanisms (Gaube et al., 2015), wind work and the influence of ocean currents on the atmosphere (Chelton et al., 2004; Chelton and Xie, 2010; O'Neill et al., 2010; Frenger et al., 2013; Renault et al., 2016b, 2018).
- **Ocean-Atmosphere-Biosphere Interactions**: Wind-driven ocean upwelling and mesoscale/submesoscale features play an important role in the availability of nutrients in the mixed layer, and, therefore on ocean productivity and ecosystems (Gaube et al., 2014; Renault et al., 2016a). Interactions of orographic jets and ocean currents can also impact ocean productivity (Xie et al., 2005). Combining WaCM surface currents and winds with ocean color data will advance our understanding of these interactions.
- **Ocean-Atmosphere-Cryosphere Interactions**: Fresh water melting from ice sheets that occurs in the upper layer of the ocean and its pathway into lower latitudes will depend on synoptic winds. The dynamics of sea ice will reflect and influence the circulation of the polar oceans as sea-ice cover continues to evolve. By measuring surface currents, winds, and sea ice motion, WaCM will make a unique contribution to understanding the evolving cryosphere.

These applications are a subset of the many identified in other white papers in this OceanObs review (Villas Boas et al., 2019). WaCM shares some similarities with SKIM (Ardhuin, 2019) and SEASTAR, also in this OceanObs review. SKIM will have smaller random errors, but, due to a narrow swath and gaps, will have different resolution capabilities than WaCM (Ardhuin et al., 2018). Unlike WaCM, SKIM will not measure winds, but provides estimates of surface currents and surface wave spectra. SEASTAR will have high spatial resolution and accuracy, but its

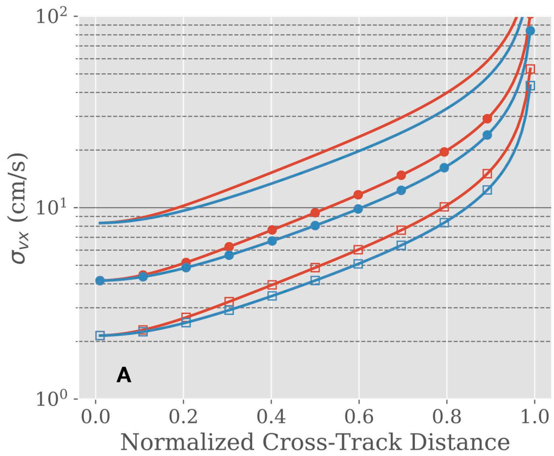

FIGURE 2 | Velocity component error as a function of the normalized cross-track distance from nadir in the **(A)** along-track (σ_{vx}) direction (roughly North) and **(B)** across-track (σ_{vy}) direction (roughly East),for antenna lengths of 4 m (read), and 5 m (blue). The peak output power is 100 Watts (solid line), 400 Watts (circles), and 1.5 kWatts (squares). From Rodriguez (2018).

coverage will be limited to coastal regions. It is clear that the three mission concepts will be highly complimentary.

In addition to purely scientific uses, we expect the data provided by WaCM to be of use for many operational, civil, and commercial applications. As detailed in Bourassa et al. (2019), scatterometers are a vital input to global numerical weather forecasting. While the scatterometer constellation continues to grow, the community recommendation for sampling sufficient to characterize diurnal and semi-diurnal observations has not been achieved. The data provided by WaCM will help improve the sampling, especially if it is not in a sun-synchronous orbit. Marine debris (Maximenko et al., 2019) is another area of application that will benefit greatly by the availability of readily available surface currents and winds. Marine debris, and other marine pollution, such as oil spills, pose an environmental challenge that is worsening in a rapidly industrializing world. Debris is hard to detect using remote sensing, and it is expected that, since its dispersal is governed by surface winds and currents, availability of the variables on a regular basis will improve greatly the ability to forecast debris and surfactant trajectories and accumulation points. The monitoring of coastal winds and currents plays an important role in shipping and coastal safety (Chang et al., 2009), and in the assessment and management of coastal fisheries. The very high resolution winds provided by WaCM in the coastal region will fill a significant gap, since current systems are generally restricted to distances from shore that can be as large as 25 km. Finally, the ability to provide wide swath imagery together with radial velocity measurements will provide a significant benefit to monitoring of the rapidly changing sea ice cover and help in the tracking of icebergs, which present a danger to shipping and are also of interest for climate monitoring (Long, 2016).

AUTHOR CONTRIBUTIONS

ER led the writing, and editing of the paper. All authors contributed equally to writing sections and revising the manuscript. All authors have approved the submitted version.

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REFERENCES

Alford, M. H., MacKinnon, J. A., Simmons, H., and Nash, J. (2014). Near-inertial internal gravity waves in the ocean. *Annu. Rev. Mar. Sci.* 8, 1–29. doi: 10.1146/annurev-marine-010814-015746

Ardhuin, F. (2019). SKIM, an ESA satellite mission for exploring global ocean currents and waves. *Front. Mar. Sci.* 6:209. doi: 10.3389/fmars.2019.00209

Ardhuin, F., Aksenov, Y., Benetazzo, A., Bertino, L., Brandt, P., Caubet, E., et al. (2018). Measuring currents, ice drift, and waves from space: the Sea surface KInematics Multiscale monitoring (SKIM) concept. *Ocean Sci.* 14, 337–354. doi: 10.5194/os-14-337-2018

Bao, Q., Dong, X., Zhu, D., Lang, S., and Xu, X. (2015). The feasibility of ocean surface current measurement using pencil-beam rotating scatterometer. *IEEE J. Sel. Top. Appl. Earth Observ. Remote Sens.* 8, 3441–3451. doi: 10.1109/JSTARS.2015.2414451

Bonjean, F., and Lagerloef, G. (2002). Diagnostic model and analysis of the surface currents in the tropical Pacific Ocean. *J. Phys. Oceanogr.* 32, 2938–2954. doi: 10.1175/1520-0485(2002)032<2938:DMAAOT>2.0.CO;2

Bourassa, M. A., and McBeth-Ford, K. (2010). Uncertainty in scatterometer-derived vorticity. *J. Atmos. Oceanic Technol.* 27, 594–603. doi: 10.1175/2009JTECHO689.1

Bourassa, M. A., Meissner, T., Cerovecki, I., Chang, P., De Chiara, G., Donlon, C., et al. (2019). Remotely sensed winds and wind stresses for marine forecasting and ocean modeling. *Front. Mar. Sci.* 6:443. doi: 10.3389/fmars.2019.00443

Chang, P. S., Jelenak, Z., Sienkiewicz, J. M., Knabb, R., Brennan, M. J., Long, D. G., et al. (2009). Operational use and impact of satellite remotely sensed ocean surface vector winds in the marine warning and forecasting environment. *Oceanography* 22, 194–207. doi: 10.5670/oceanog.2009.49

Chapron, B., Collard, F., and Ardhuin, F. (2005). Direct measurements of ocean surface velocity from space: interpretation and validation. *J. Geophys. Res. Oceans* 110. doi: 10.1029/2004JC002809

Chelton, D. B., Schlax, M. G., Freilich, M. H., and Milliff, R. F. (2004). Satellite measurements reveal persistent small-scale features in ocean winds. *Science* 303, 978–983. doi: 10.1126/science.1091901

Chelton, D. B., Schlax, M. G., Samelson, R. M., Farrar, J. T., Molemaker, M. J., McWilliams, J. C., et al. (2018). Prospects for future satellite estimation of small-scale variability of ocean surface velocity and vorticity. *Prog. Oceanogr.* 173, 256–350. doi: 10.1016/j.pocean.2018.10.012

Chelton, D. B., and Xie, S.-P. (2010). Coupled ocean-atmosphere interaction at oceanic mesoscales. *Oceanography* 23, 52–69. doi: 10.5670/oceanog.2010.05

Clarke, A., and Van Gorder, S. (2018). The relationship of near-surface flow, stokes drift and the wind stress. *J. Geophys. Res. Oceans* 123, 4680–4692. doi: 10.1029/2018JC014102

de Kloe, J., Stoffelen, A., and Verhoef, A. (2017). Improved use of scatterometer measurements by using stress-equivalent reference winds. *IEEE J. Sel. Top. Appl. Earth Observ. Remote Sens.* 10, 2340–2347. doi: 10.1109/JSTARS.2017.2685242

Draper, D. W., and Long, D. G. (2004). Evaluating the effect of rain on SeaWinds scatterometer measurements. *J. Geophys. Res. Oceans* 109. doi: 10.1029/2002JC001741

Durand, M., Fu, L.-L., Lettenmaier, D., Alsdorf, D., Rodriguez, E., and Esteban-Fernandez, D. (2010). The surface water and ocean topography mission: observing terrestrial surface water and oceanic submesoscale eddies. *Proc. IEEE* 98, 766–779. doi: 10.1109/JPROC.2010.2043031

Frenger, I., Gruber, N., Knutti, R., and Münnich, M. (2013). Imprint of southern ocean eddies on winds, clouds and rainfall. *Nat. Geosci.* 6:608. doi: 10.1038/ngeo1863

Gaube, P., Chelton, D. B., Samelson, R. M., Schlax, M. G., and O'Neill, L. W. (2015). Satellite observations of mesoscale eddy-induced ekman pumping. *J. Phys. Oceanogr.* 45, 104–132. doi: 10.1175/JPO-D-14-0032.1

Gaube, P., McGillicuddy, D. J., Chelton, D. B., Behrenfeld, M. J., and Strutton, P. G. (2014). Regional variations in the influence of mesoscale eddies on near-surface chlorophyll. *J. Geophys. Res. Oceans* 119, 8195–8220. doi: 10.1002/2014JC010111

Goldstein, R. M., Barnett, T. P., and Zebker, H. A. (1989). Remote sensing of ocean currents. *Science* 246, 1282–1285. doi: 10.1126/science.246.4935.1282

Hodges, R., and Zawadzki, M. (2012). "Ka-band reflectarray for interferometric SAR altimeter," in *Antennas and Propagation Society International Symposium (APSURSI), 2012 IEEE* (Monterey, CA: IEEE), 1–2.

Johannessen, J., Chapron, B., Collard, F., Kudryavtsev, V., Mouche, A., Akimov, D., et al. (2008). Direct ocean surface velocity measurements from space: improved quantitative interpretation of Envisat ASAR observations. *Geophys. Res. Lett.* 35. doi: 10.1029/2008GL035709

Lagerloef, G., Mitchum, G., Lukas, R., and Niiler, P. (1999). Tropical Pacific near-surface currents estimated from altimeter, wind, and drifter data. *J. Geophys. Res. Oceans* 104, 23313–23326. doi: 10.1029/1999JC900197

Lin, C.-C., Lengert, W., and Attema, E. (2017). Three generations of c-band wind scatterometer systems from ers-1/2 to metop/ascat, and metop second generation. *IEEE J. Sel. Top. Appl. Earth Observ. Remote Sens.* 10, 2098–2122. doi: 10.1109/JSTARS.2016.2616166

Lindsley, R. D., Anderson, C., Figa-Saldaña, J., and Long, D. G. (2016). A parameterized ASCAT measurement spatial response function. *IEEE Trans. Geosci. Remote Sens.* 54, 4570–4579. doi: 10.1109/TGRS.2016.2544835

Long, D. G. (2016). Polar applications of spaceborne scatterometers. *IEEE J. Sel. Top. Appl. Earth Observ. Remote Sens.* 10, 2307–2320. doi: 10.1109/JSTARS.2016.2629418

Masuko, H., Okamoto, K., Shimada, M., and Niwa, S. (1986). Measurement of microwave backscattering signatures of the ocean surface using x band and ka band airborne scatterometers. *J. Geophys. Res. Oceans* 91, 13065–13083. doi: 10.1029/JC091iC11p13065

Maximenko, N., et al. (2019). Towards the integrated marine debris observing system. *Front. Mar. Sci*. 6:447. doi: 10.3389/fmars.2019.00447

McWilliams, J. (2016). Submesoscale currents in the ocean. *Proc. R. Soc. A* 472:20160117. doi: 10.1098/rspa.2016.0117

Morey, S., Wienders, N., Dukhovskoy, D., and Bourassa, M. (2018). Measurement characteristics of near-surface currents from ultra-thin drifters, drogued drifters, and HF radar. *Remote Sens.* 10:1633. doi: 10.3390/rs10101633

National Academies of Sciences, Engineering, and Medicine (2018). *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space.* Washington, DC: The National Academies Press.

O'Neill, L. W., Chelton, D. B., and Esbensen, S. K. (2010). The effects of SST-induced surface wind speed and direction gradients on midlatitude surface vorticity and divergence. *J. Clim.* 23, 255–281. doi: 10.1175/2009JCLI2613.1

Plagge, A., Vandemark, D., and Long, D. (2009). Coastal validation of ultra-high resolution wind vector retrieval from QuikSCAT in the Gulf of Maine. *IEEE Geosci. Remote Sens. Lett.* 6, 413–417. doi: 10.1109/LGRS.2009.2014852

Renault, L., Deutsch, C., McWilliams, J. C., Frenzel, H., Liang, J.-H., and Colas, F. (2016a). Partial decoupling of primary productivity from upwelling in the California Current system. *Nat. Geosci.* 9, 505–508. doi: 10.1038/ngeo2722

Renault, L., McWilliams, J. C., and Gula, J. (2018). Dampening of submesoscale currents by air-sea stress coupling in the Californian Upwelling System. *Sci. Rep.* 8:13388. doi: 10.1038/s41598-018-31602-3

Renault, L., Molemaker, J., McWilliams, J., Shchepetkin, A., Lemarie, F., Chelton, D., et al. (2016b). Modulation of wind work by oceanic current interaction with the atmosphere. *J. Phys. Oceanogr.* 46, 1685–1704. doi: 10.1175/JPO-D-15-0232.1

Rocha, C. B., Chereskin, T. K., Gille, S. T., and Menemenlis, D. (2016). Mesoscale to submesoscale wavenumber spectra in Drake Passage. *J. Phys. Oceanogr.* 46, 601–620. doi: 10.1175/JPO-D-15-0087.1

Rodriguez, E. (2018). On the optimal design of Doppler scatterometers. *Remote Sens.* 10:1765. doi: 10.3390/rs10111765

Rodriguez, E., Wineteer, A., Perkovic-Martin, D., Gal, T., Stiles, B., Niamsuwan, N., et al. (2018). Estimating ocean vector winds and currents using a Ka-band pencil-beam doppler scatterometer. *Remote Sens.* 10:576. doi: 10.3390/rs10040576

Rouault, M. J., Mouche, A., Collard, F., Johannessen, J. A., and Chapron, B. (2010). Mapping the Agulhas Current from space: An assessment of ASAR surface current velocities. *J. Geophys. Res. Oceans* 115. doi: 10.1029/2009JC006050

Stammer, D., and Cazenave, A. (2017). *Satellite Altimetry Over Oceans and Land Surfaces*. Boca Raton, FL: CRC Press.

Villas Boas, A. B., Ardhuin, F., Ayet, A., Bourassa, M. A., Brandt, P., Chapron, B., et al. (2019). Integrated observations and modeling of winds, currents, and waves: requirements and challenges for the next decade. *Front. Mar. Sci.* 6:425. doi: 10.3389/fmars.2019.00425

Vogelzang, J., and Stoffelen, A. (2016). ASCAT Ultrahigh-resolution wind products on optimized grids. *IEEE J. Sel. Top. Appl. Earth Observ. Remote Sens.* 10, 2332–2339. doi: 10.1109/JSTARS.2016.2623861

Wentz, F., Ricciardulli, L., Rodriguez, E., Stiles, B., Bourassa, M., Long, D., et al. (2017). Evaluating and extending the ocean wind climate data record. *IEEE J. Sel. Top. Appl. Earth Observ. Remote Sens.* 10, 2165–2185. doi: 10.1109/JSTARS.2016.2643641

Xie, S.-P., Xu, H., Kessler, W., and Nonaka, M. (2005). Air–sea interaction over the Eastern Pacific Warm Pool: gap winds, thermocline dome, and atmospheric convection. *J. Clim.* 18, 5–20. doi: 10.1175/JCLI-3249.1

Yurovsky, Y., Kudryavtsev, V. N., Grodsky, S. A., and Chapron, B. (2016). Ka-band dual copolarized empirical model for the sea surface radar cross section. *IEEE Geosci. Remote Sens.* 55, 1–19. doi: 10.1109/TGRS.2016.2628640

Yurovsky, Y. Y., Kudryavtsev, V. N., Chapron, B., and Grodsky, S. A. (2018). Modulation of Ka-band Doppler radar signals backscattered from the sea surface. *IEEE Trans. Geosci. Remote Sens.* 56, 2931–2948. doi: 10.1109/TGRS.2017.2787459

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More Than 50 Years of Successful Continuous Temperature Section Measurements by the Global Expendable Bathythermograph Network, Its Integrability, Societal Benefits, and Future

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The first eXpendable BathyThermographs (XBTs) were deployed in the 1960s in the North Atlantic Ocean. In 1967 XBTs were deployed in operational mode to provide a continuous record of temperature profile data along repeated transects, now known as the Global XBT Network. The current network is designed to monitor ocean circulation and boundary current variability, basin-wide and trans-basin ocean heat transport, and global and regional heat content. The ability of the XBT Network to systematically map the upper ocean thermal field in multiple basins with repeated trans-basin sections at eddy-resolving scales remains unmatched today and cannot be reproduced at present by any other observing platform. Some repeated XBT transects have now been continuously occupied for more than 30 years, providing an unprecedented long-term climate record of temperature, and geostrophic velocity profiles that are used to understand variability in ocean heat content (OHC), sea level change, and meridional ocean heat transport. Here, we present key scientific advances in understanding the changing ocean and climate system supported by XBT observations. Improvement in XBT data quality and its impact on computations, particularly of OHC, are presented. Technology development for probes, launchers, and transmission techniques are also discussed. Finally, we offer new perspectives for the future of the Global XBT Network.

Keywords: expendable bathythermographs, surface currents, subsurface currents, meridional heat transport, ocean heat content, sea level, extreme weather

INTRODUCTION

EXpendable BathyThermographs (XBTs) are instruments that provide the simplest and most cost-efficient solution for frequently obtaining temperature profiles along fixed transects of the upper thousand meters of the ocean. XBTs have been historically deployed by navies, research vessels, and merchant ships. The first XBT probes were tested in 1959, and systematic deployment of XBTs began in the mid to late 1960s. XBTs thereafter became the largest source of data for the upper ocean thermal record during the 1970s−1990s, with ∼89,000 XBTs deployed in 1990. XBTs thus provide one of the longest available historical records of upper ocean temperature profiles (to ∼1,000 m depth). Currently, XBTs deployed along fixed transects are grouped into what constitutes the Global XBT Network (**Figure 1**, top panel). During the past 10 years, 15,000–20,000 XBTs have been deployed annually. Most of the XBTs being currently deployed are from the Deep Blue type, which can reach depths of 800 m (Cheng et al., 2014).

Observations from the Global XBT Network provide repeated sections of temperature along fixed transects that cross regions that are critical for monitoring, understanding, and assessing surface and subsurface dynamical processes that occur in the upper ocean. Data from the Global XBT Network have been used extensively to estimate variability and changes in near-surface ocean properties (e.g., heat content) and dynamics (e.g., Levitus et al., 2012). XBT observations informed much of what is known about variability and changes in global and regional upper-ocean heat content (OHC) before the near-global Argo profiling float array was implemented (Riser et al., 2016; Jayne et al., 2017). XBT observations are extremely valuable in near-coastal regions and in some areas of the open ocean where they are the sole source of repeated hydrographic observations that resolve mesoscale features for assessing transports.

The current Global XBT Network collects observations at spatial and temporal scales that cannot feasibly be duplicated by other observational platforms. While platforms such as profiling floats (Riser et al., 2016) and underwater gliders (Rudnick, 2016) now provide temperature profiles, they cannot occupy repeated, mesoscale-resolving, trans-ocean basin transects across major currents on the time scales that are regularly sampled using XBTs from fast-moving ships. Observations from XBTs and from other profiling platforms should be seen as complementary. For example, XBTs provide targeted observations in specific regions, while Argo floats provide background information needed to understand the processes that lead to the variability observed by XBT observations (**Figure 2**). In addition, collocated observations from XBTs and other components of the Global Ocean Observing System (GOOS) can be used to identify and assess potential errors or biases within the observing system.

XBT observations are currently mainly used to:

1) Monitor the state and spatial and temporal variability of key surface and subsurface ocean currents and boundary currents, including their transport;
2) Monitor the state and variability of the Meridional Heat Transport (MHT) and Meridional Overturning Circulation (MOC) across ocean basins;
3) Provide upper ocean thermal observations to estimate global and regional OHC in areas undersampled by other observational platforms;
4) Initialize and validate Ocean Forecasting Systems; and
5) Provide constraints through data assimilation for ocean reanalysis hindcasts.

The two spatial modes of XBT deployment currently used in the Global XBT Network are:

1. **High Density or High Resolution (HD/HR)**: Usually four or more repetitions are conducted annually along a fixed transect with an average of one XBT deployment about every 10–50 km along the ship track (35 XBT deployments per day at a ship speed of 20 kts). This mode is aimed at obtaining high spatial resolution in a single realization to resolve the spatial structure of mesoscale eddies, fronts, and boundary currents. These transects are designed to resolve boundary currents and to estimate basin-scale geostrophic velocity and mass and heat transports, including the MOC, and heat transport. This is currently the most widely used deployment mode.
2. **Frequently Repeated (FR)**: Twelve or more repetitions are conducted annually along a fixed transect, with six or more XBT deployments performed daily along the transect every 100–150 km. This mode is aimed at obtaining repeat surveys along those transects where there is high temporal variability. This sampling mode is designed to produce well-resolved monthly time series that observe specific features of the thermal structure (e.g., thermocline ridges) or that obtain

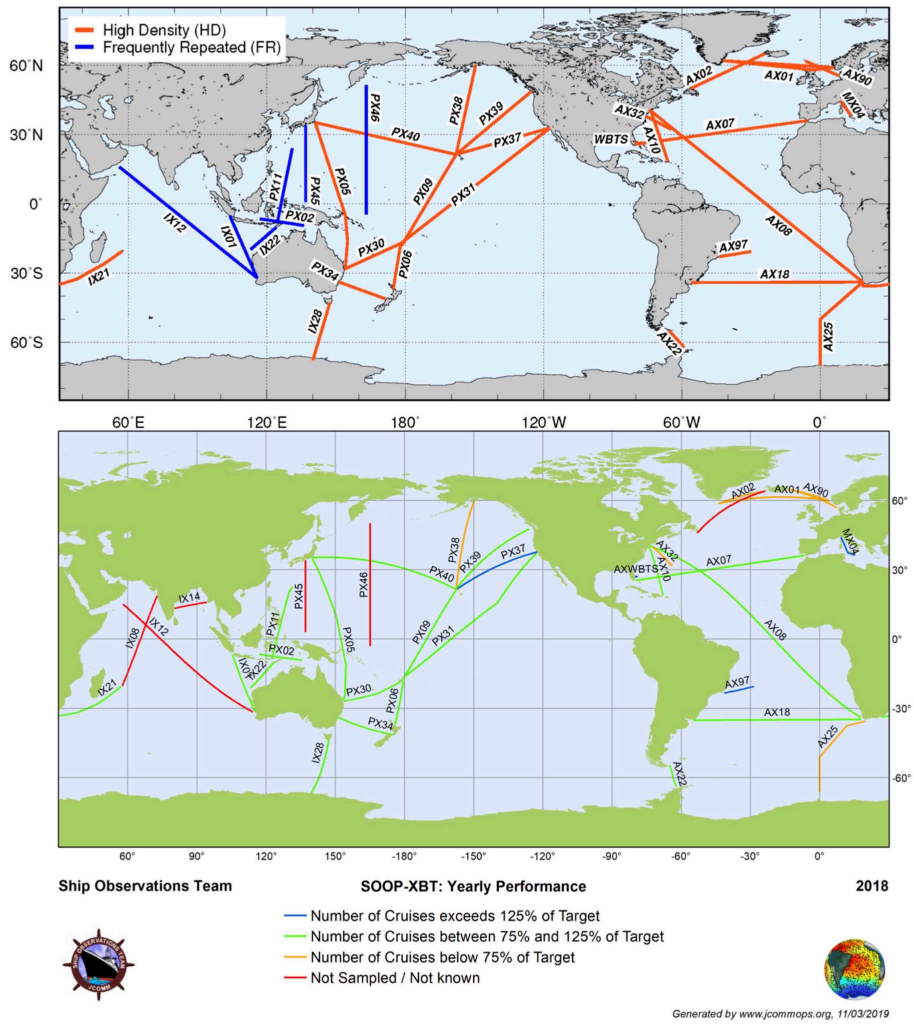

FIGURE 1 | (Top) Location of the HD/HR and FR XBT transects recommended by the XBT Science Team during the 5th Science Workshop held in October 2016. **Table 1** provides a detailed explanation of each transect. **(Bottom)** Annual performance of the XBT network. Targets are set by the XBT Science Team and compared to realization numbers for each transect. The KPI defined by the total number of realization numbers divided by the number of all targeted realizations is 82% for 2018.

samples where intraseasonal variability is strong (e.g., the Indonesian Throughflow).

The currently operated transects (**Figure 1**, top panel) follow recommendations from the international review of the global upper ocean thermal network (Smith et al., 2001), OceanObs'99, OceanObs'09 (Goni et al., 2010), and recent recommendations from the XBT Science Team. Profiles from about 90% of the XBT deployments are transmitted in near real-time into the Global Telecommunication System (GTS), making up ∼15% of the current real-time vertical temperature profile observations (not including the continuous temperature profiles made by some moorings).

Some XBT transects have been in operation for more than 30 years, thereby providing unique and valuable climate records. For example, AX10 (New York to San Juan) has provided key information about the variability in upper ocean temperature within the Gulf Stream for more than 55 years (Molinari, 2004). PX06 (Auckland to Fiji) has been occupied since 1986 and was the first transect sampled in HD/HR mode; it has now been sampled more than 90 times over 30 years. In the Indian and Pacific oceans, the FR transects IX01 (Western Australia to Java) and PX02 (Darwin, Australia to Indonesia) have been sampled for more than 35 years. Since the implementation of the Argo array in 1999 to sample the ocean interior (Gould et al., 2004; Riser et al., 2016), the focus of the XBT array has been to primarily monitor boundary currents and trans-basin sections that capture the meridional transport of heat and mass.

This review presents the current state of the Global XBT Network, major scientific advances resulting from the decades-long XBT record, and synergy between the Global XBT Network and other components of the observing system. Examples of how the XBT network contributes to both operational oceanography

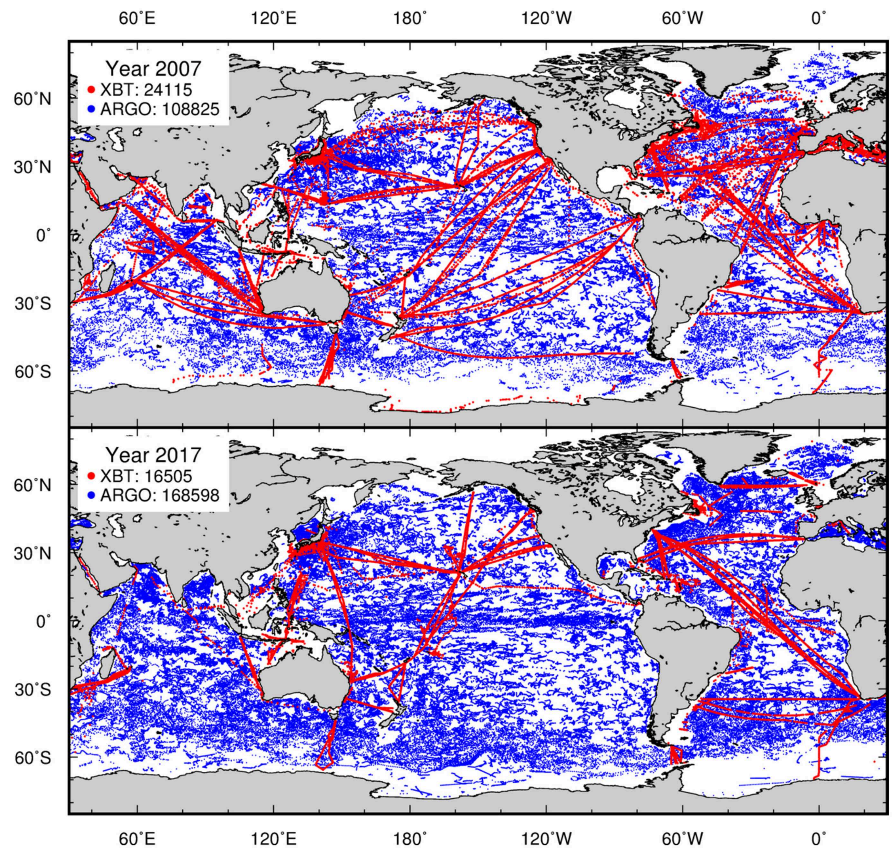

FIGURE 2 | Location of XBT (red) and Argo float (blue) measurements during the years 2007 **(Top)** and 2017 **(Bottom)** that show the difference of spatial sampling produced by these observing platforms. The numbers indicate the observations made by each platform during these 2 years.

and monitoring the state of the ocean, particularly with respect to the MOC, OHC, and sea level change, and extreme weather events, are also highlighted.

XBT OPERATIONAL AND SCIENTIFIC OVERSIGHT

XBT operations are coordinated on a global scale by the Ship Of Opportunity Programme Implementation Panel (SOOPIP), a network of the Ship Observations Team (SOT) which operates under the framework of the Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) of the World Meteorological Organization (WMO) and UNESCO's Intergovernmental Oceanographic Commission (IOC). The JCOMM Observations Programme Support Center (JCOMMOPS) is tasked with monitoring the operational efforts of the SOOPIP. It also implements Key Performance Indicators (KPI) and status maps for the current Global XBT network, re/defined by the international community (**Figure 1**, bottom panel).

The Global XBT Network is a key component of GOOS that addresses themes related to climate, operational services, and marine ecosystem health. The network directly or indirectly measures Essential Ocean and Climate Variables, such as sea surface temperature, subsurface temperature, surface and subsurface currents, and ocean surface heat flux. The scientific oversight and justification is provided and assessed by the XBT Science Team.

Scientific aspects of XBT observations are discussed within the XBT Science Team, which was created in 2011 and consists of more than 30 experts and scientists from 19 institutions and 10 countries. The focus of this team is to:

- Provide a voice in the scientific community to communicate XBT-related results;
- Organize meetings of the XBT community to discuss scientific advances in the use of XBT observations;
- Enhance international scientific collaboration;
- Make recommendations and prioritize transects of the XBT network;
- Make recommendations on XBT data management;
- Cultivate links to active and recognized scientific and operational panels of other observing platforms.

The XBT Science Team website[1] provides easy access to XBT data, XBT-derived products and indicators, and other XBT-related scientific and operational information. It also brings scientists together to highlight the uses of XBT data, including upper ocean thermal structure and variability, ocean currents, and heat transport.

[1] www.aoml.noaa.gov/phod/goos/xbtscience

In addition to the XBT Science Team, scientists and operators involved in the XBT network participate in international panels that address many aspects of XBT operations, data management, and science. These panels provide a wide range of recommendations geared toward interdisciplinary and complementary studies, the continuous reporting of research highlights, and improvement of the XBT network integration with the GOOS. Some of these panels are:

- SOOPIP: This panel coordinates the operational and data management standards for the implementation and maintenance of the Global XBT Network from volunteer ships.
- IQuOD: The International Quality controlled Ocean Database (IQuOD) project focuses on the creation and distribution of a complete, high quality single ocean profile repository, including metadata, and assigned uncertainties, mostly for use in ocean climate research applications, data assimilation, and model evaluation[2].
- GOSUD: The Global Ocean Surface Underway Data (GOSUD) Project is an IOC program dedicated to assembling and distributing quality-controlled data sets of underway sea surface temperature and salinity observations collected by cargo ships and research vessels.
- GTSPP: The Global Temperature and Salinity Profile Program (GTSPP) provide essential subsurface climate variables of temperature and salinity profile data, as well as timely and complete data with documented quality flags. It implements internationally agreed upon quality control standards and manages ocean data in accordance with the GOOS action plan.

KEY XBT SCIENTIFIC CONTRIBUTIONS

Since the inception of the XBT network, XBT observations have led to pioneering research related to OHC, ocean current variability, and water mass and heat transports. The contributions of XBT observations to scientific research have been highlighted in thousands of publications and have also provided the basis for many student theses and dissertations. On average, about 100 peer-reviewed manuscripts that use XBT data are published annually.

XBTs have provided some of the longest continuous records of ocean currents, with many of the existing transects surpassing 30 years of uninterrupted observations across ocean basins on at least a quarterly basis. These include the surveillance of narrow boundary current regions that the global Argo array with its 3-degree spacing cannot resolve. XBTs are one of the few observational platforms capable of long-term monitoring of ocean current properties at the surface and at subsurface depths and of measuring trans-oceanic temperature sections at an eddy-resolving resolution. The maintenance of sustained temperature profile observations along these fixed transects is critical for long-term monitoring of the properties of key ocean currents and integrated transport across basins.

Scientists from the XBT community have been successful in developing and implementing novel methodologies, including multiplatform and multivariable assessments, that have become standard for monitoring and analyzing the state and variability of the ocean. In what follows, section the complementarity of XBTs with other observing platforms highlights studies that discuss the synergy of XBT transects with other components of the global observing system. Section Ocean currents, gyres, and ocean variability shows examples of how XBT monitoring has improved understanding of ocean currents, gyres, and ocean variability, while sections meridional heat transport, global and regional ocean heat content, and operational oceanography and ocean forecasts highlight MHT, global/regional OHC, and operational oceanography/ocean forecasts, respectively. Section Societal benefits of XBT observations provides an overview of the societal benefits of XBT observations, section Data management addresses XBT data management, and section Technological Improvements discusses technological improvements. Finally, section the future of the Global XBT Network presents the vision of the authors on the future of the Global XBT Network.

The Complementarity of XBTs With Other Observing Platforms

Several studies have combined XBT profiles with collocated Conductivity, Temperature, and Depth (CTD), Argo, and satellite altimetry observations to establish, for example, a statistical dynamic height relationship. By linking dynamic height to cumulative baroclinic transport across an XBT section, altimetric dynamic height can be used to extend the XBT sections into a near-continuous long-term time series of baroclinic transport. The synergy between XBT temperature profiles and sea surface height measured by satellites has been used extensively to monitor several current systems and regions, including the Antarctic Circumpolar Current (ACC) south of Tasmania (Rintoul et al., 2002), the Agulhas retroflection and ACC fronts south of Africa (Swart et al., 2008), the ACC fronts in the Drake Passage (Sprintall, 2003), the East Australian Current (Zilberman et al., 2018), across the North Pacific gyre (Roemmich and Gilson, 2001), the Brazil Current (Goni and Wainer, 2001), the North Brazil Current (Fonseca et al., 2004), the East India Coastal Currents in the Bay of Bengal (Sherin et al., 2018), the Gulf Stream (Molinari, 2011), and the Florida Current (Olson et al., 1983; Domingues et al., 2018). Section Ocean currents, gyres, and ocean variability shows examples of how XBT observations are integrated with data from other observing platforms to assess the state and variability of the ocean. The complementarity of XBT observations to data provided by other observing platforms are further shown in this issue for MHT (Frajka-Williams et al., 2019) and boundary currents (Todd et al., 2019).

Ocean Currents, Gyres, and Ocean Variability

Gulf Stream

The Gulf Stream, the Western Boundary Current (WBC) of the North Atlantic, has been linked to changes in various weather and climate phenomena, including extreme weather events over the Northwest Atlantic, the Atlantic Meridional Overturning Circulation (AMOC), and coastal sea level rise (Latif et al., 2000;

[2]www.iquod.org

Hoskins and Hodges, 2002; Joyce et al., 2009; Kelly et al., 2010; Kwon et al., 2010).

Four XBT transects monitor the Gulf Stream at different locations: AX08 (Cape Town to New York), AX10 (New York to Puerto Rico), AX32 (New York to Bermuda), and AXWBTS (Palm Beach, FL, to Grand Bahama). The first sustained time series of the position of the Gulf Stream, beginning in the early 1950s, was obtained by combining mechanical bathythermograph measurements with XBT data along AX10. These observations showed that meridional migration of the Gulf Stream is strongly correlated with the North Atlantic Oscillation (NAO) on decadal time-scales and that the meridional migration is also similar to anomalies in Gulf Stream upper layer transport and an east-west extension of the Gulf Stream southern recirculation gyre (Molinari, 2004).

The Gulf Stream between the northeastern United States and Bermuda has been surveyed for nearly 150 years. The H.M.S. *Challenger* collected the oldest documented temperature section across the Gulf Stream in 1873 (Rossby et al., 2010). Between the late 1960s and early 1970s, the US Naval Oceanographic Office made a large number of high resolution XBT sections from various passenger vessels between 40°N (the outer continental shelf) and 35°N. These data are currently being reassembled and will be archived cruise-by-cruise. Since 1977 the Global XBT Network has included XBT deployments across the shelf out to and sometimes into the Gulf Stream on a monthly basis along AX32 and in HD mode with transects AX10 and AX08. In late 1992, a program to measure upper ocean currents along the New Jersey-Bermuda section was implemented using the M/V *Oleander*, a container vessel. As part of this effort, additional XBTs are now being deployed across the Gulf Stream on a monthly basis.

A recent analysis of the 20-year time series of AX10 HD data (**Figure 3A**) shows that the Gulf Stream experiences strong north-south shifts, which can exceed two degrees of latitude on seasonal time scales. However, the current itself has not exhibited significant long-term trends in location (**Figure 3B**) or in transport (**Figure 3C**). Ongoing research indicates that 20 years of measurements using AX10 data show that below the seasonal mixed layer the largest temperature variability in the Gulf Stream occurs between 300 and 600 m depth. This is important because subtropical mode waters are found within this depth range. Geostrophic velocity estimated from each AX10 section using temperature measurements from XBTs and salinity inferred from the historical T-S relationship (Goes et al., 2018) shows that the temporal variations in the XBT-derived geostrophic velocity estimates are vertically coherent. Combining AX10 observations with satellite altimetry observations has also resulted in improved understanding of Gulf Stream changes over a larger region (50°-80°W). During 1993–2016, the Gulf Stream was found to experience a strong southward shift east of 65°W after passing the New England Seamount chain (**Figure 4A**). This southward shift was accompanied by a weakening of the Gulf Stream (**Figures 4B,C**). West of 70°W, however, the observed

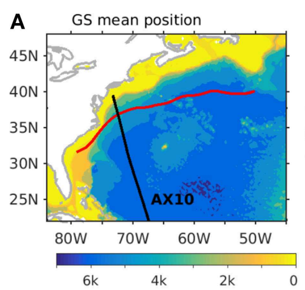

FIGURE 3 | (A) Time-mean Gulf Stream position from satellite altimetry (red) and the location of the XBT AX10 transect (black). **(B)** Gulf Stream position from AX10 in degree latitude. **(C)** Gulf Stream transport in the upper 800 m water column from AX10 (referenced to 800 m); units are Sverdrups (10^6 m^3 s^{-1}). The background color shows the bottom depth.

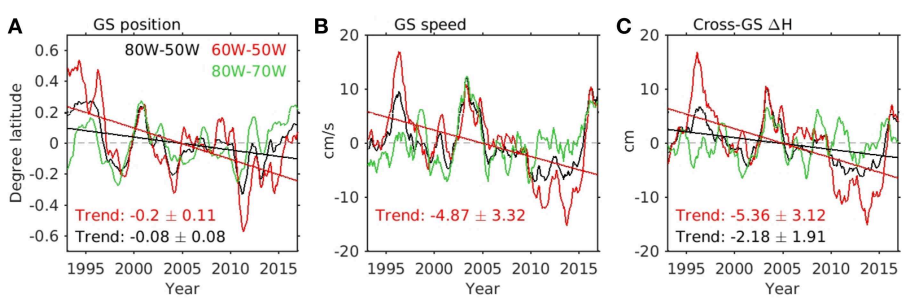

FIGURE 4 | Zonally averaged Gulf Stream **(A)** position, **(B)** speed, and **(C)** cross-front sea surface height (SSH) difference (proxy for transport) derived from satellite altimetry.

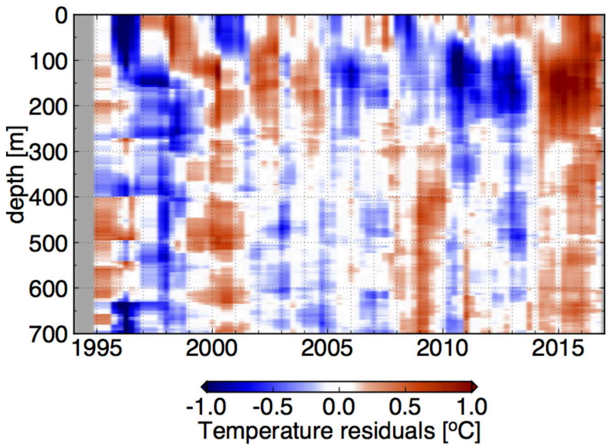

FIGURE 5 | Depth-time diagram of the average temperature residuals (seasonal cycle removed and one 1-year low-pass filter applied) in the Florida Straits using subsurface temperature profile data derived from 1,925 XBT profiles (AX07 and AXWBTS) and 541 CTD casts sampled during 1995–2016.

trends during 1993–2006 were very weak. This type of study is important because the sea surface temperature (SST) gradient associated with the Gulf Stream contributes significantly to the growth of midlatitude storm activity, storm tracks, and intensity (Chang et al., 2002; Kushnir et al., 2002; Nakamura et al., 2004).

Florida Current

The Florida Current is the WBC that feeds into the Gulf Stream and carries both the return flow from the subtropical wind-driven gyre and the upper branch of the AMOC. The Florida Current is routinely monitored by two XBT transects: AX07 (Miami to Gibraltar) and AXWBTS. While the AMOC has long been recognized as an important component of the climate system, changes in the intensity of the Florida Current transport and heat carried by the current have also been recently acknowledged as key drivers of regional sea level changes along the US East Coast (Ezer, 2013; Domingues et al., 2016). An analysis of XBT profiles from these transects reveals substantial year-to-year changes in the Florida Current temperature, which can exceed ±1°C over the full time record (**Figure 5**). The time series reveals that temperature anomalies are mostly coherent throughout the entire water column (e.g., late 2015), although ∼30% of the time the anomalies above and below 100 m have opposite signs (e.g., early 1997). XBT data also revealed an unprecedented warming of the Florida Current during 2014–2015, which followed a relatively cold period in 2010–2013. During the 2014–2015 event, the entire water column in the Florida Straits was ∼0.5°C warmer than average conditions. As discussed in section regional sea level changes, these changes are key drivers of coastal sea level anomalies in the region. Temperature changes in the Florida Current are also found to be uncorrelated with changes in the intensity of its flow (Domingues et al., 2018). These phases of warming and cooling of the Florida Current have important impacts on regional sea level changes along the US Southeast Coast.

Brazil Current

The Brazil Current (BC) is the WBC of the South Atlantic subtropical gyre. There are two XBT transects that cross the BC: AX18 (Buenos Aires to Cape Town) at 34°S and AX97 (Rio de Janeiro to Ilha da Trindade) at 22°S. Started in 2002 and 2004, respectively, AX18 and AX97 are the longest continuous efforts to assess the structure and variability of the BC. The BC is of key importance in closing the mass budget in the South Atlantic, since it is the WBC that closes the subtropical gyre, transporting waters from subpolar regions, thus constituting an integral part of the AMOC. Until the implementation of these two XBT transects, most of the BC observations relied on sparse cruise data, short period mooring deployments, or models. A recent study (Lima et al., 2016) used geostrophic velocity fields constructed from AX97 data to show that models generally misrepresent the structure of the variability of this current, simulating it as too deep, and too wide. AX97 transects have resolved the high mesoscale variability associated with the BC that can manifest in inshore or offshore states, depending on transient eddies and the semi-permanent Cape of São Tomé eddy (Mill et al., 2015). During the summer of 2009–2010, an extreme warm SST event (>3°C) was identified near 22°S off the coast of Brazil, which was associated with atmospheric teleconnections from a Central Niño event in the Pacific (Majumder et al., 2019). During the warm SST event, the XBT-derived geostrophic BC transport (12 Sv) was three times larger than average. This anomalous transport was physically linked to increased coastal upwelling and baroclinicity in the region (Goes et al., 2019). These processes enhance the SST gradient across the BC off Cabo Frio, Brazil, which generates wind convergence/curl and thickens the atmospheric boundary layer, impacting local weather and precipitation (e.g., Pezzi et al., 2016). Future work will include assessing the subtropical gyre variability and BC frontal changes to regional weather patterns.

East India Coastal Current in the Bay of Bengal

The upper layer circulation of the Bay of Bengal (BoB) is known to have strong seasonal variability (Eigenheer and Quadfasel, 2000). During the northeast monsoon, the East India Coastal Current (EICC) is the WBC of the BoB and flows equatorward along the east coast of India to Sri Lanka. Sherin et al. (2018) used 27 years of repeated XBT sections that cross the western (Chennai to Port Blair) and northwestern (Kolkata to Port Blair) regions of the BoB to study the EICC and its interannual variability. The EICC was found to be seasonally reversing, flowing poleward from February to July with a transport of 5 Sv and then flowing equatorward from October to December with a transport of 3 Sv. In March, 7 Sv in the EICC flows northeastward in the northwestern BoB. Weak northwestward flow (2 Sv at most) occurs during the remainder of the calendar year. The Indian Ocean Dipole (IOD) is found to have a significant influence on EICC variability. Remote wind forcing from the equatorial Indian Ocean associated with the EICC generates a northward (southward) anomalous transport of 5 Sv (7 Sv) during winter of positive (negative) IOD events (Sherin et al., 2018).

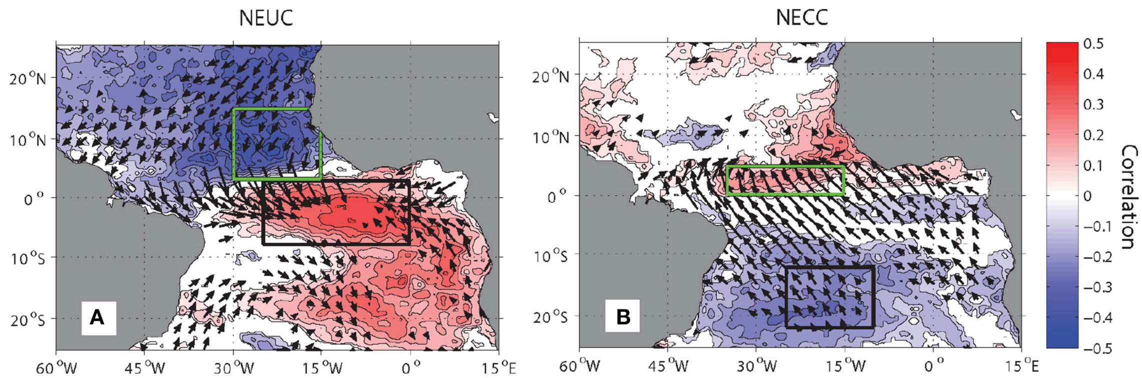

FIGURE 6 | Simultaneous correlation of monthly anomalies of tropical Atlantic SST (contour) and pseudo wind stress (vectors) with the transport of **(A)** North Equatorial Undercurrent (NEUC) and **(B)** North Equatorial Countercurrent (NECC) at interannual timescales. Anomalies are calculated relative to the monthly means. The boxes represent the regions of maximum correlation.

Tropical Atlantic Current System

The AX08 transect monitors and assesses the tropical Atlantic system of surface and subsurface currents and countercurrents at ∼23°W. AX08 transect data and satellite-derived sea height fields revealed that altimetry data alone could not be used to identify and monitor all currents in the tropical Atlantic, particularly the undercurrents (Goni and Baringer, 2002). In a more recent study, Goes et al. (2013a) combined XBT data with historical temperature-salinity relationships, altimetric sea level anomalies, and Argo-based steric height data to estimate density and velocity properties of the tropical Atlantic eastward currents for the entire altimetric period (1992-present). Goes et al. (2013a) associated the variability of the North Equatorial Undercurrent (NEUC) and North Equatorial Countercurrent (NECC) with the main modes of interannual variability in the tropical Atlantic (**Figure 6**), particularly the Atlantic Meridional Mode (AMM) and associated excursions of the Intertropical Convergence Zone. The NECC and NEUC transports were found to be out-of-phase; the NECC (NEUC) is associated with positive (negative) AMM and led by the strengthening (weakening) of the trade winds. Although satellite altimetry measurements have sufficient temporal and spatial resolution to resolve most of the highly variable surface processes near the equator, the XBT data were critical in sampling the vertical and meridional structure of the subsurface currents, which are generally between 200 and 300 m deep and 100–150 km wide (Goes et al., 2013a).

The East Australian Current, the East Auckland Current, and the Tasman Sea

XBT transects PX30 (Brisbane to Fiji) and PX34 (Sydney to Wellington) cross the East Australian Current (EAC), the WBC of the South Pacific gyre. XBT transect PX06 (Auckland to Fiji) crosses the East Auckland Current (EAuC). These transects are among the longest running HR lines in the Global XBT Network and have now been sampling along near-repeat transects for over 30 years (**Table 1**).

Geostrophic velocity estimates obtained by combining XBT and satellite altimetry data have shown that the eastward flow from the separated EAC occurs in distinct permanent filaments (Ridgway and Dunn, 2003; Ridgway et al., 2008), demonstrating the banded nature of the mean velocity field. Hill et al. (2011) showed that southward transport in the Tasman Sea is strongly anti-correlated with the eastward transport of the Tasman Front (PX06) north of New Zealand. Moreover, a multi-decadal southward shift in the Southern Hemisphere westerly winds has resulted in less eastward transport in the Tasman Front and greater southward transport in the EAC Extension. This work, following a previous analysis by Roemmich et al. (2005), sheds light on not only long-term temperature and salinity trends in the Tasman Sea but also the ecosystem impacts of climate change in the EAC system. These XBT data have significantly contributed to our understanding of the mass and heat budgets in the Tasman region and the formation, spreading, characteristics, and variability of South Pacific Subtropical Mode Water (Roemmich and Cornuelle, 1992; Roemmich et al., 2005; Tsubouchi et al., 2007; Holbrook and Maharaj, 2008).

Considerable effort over the past 10 years has focused on expanding our knowledge of the temporal variability of the EAC and EAuC transports at interannual to decadal time scales, although uncertainties remain. The XBT-derived transport time-series show interannual variability with a period of about 4 years and a decadal trend toward lower eastward transport (Hill et al., 2008). This trend is consistent with changes in the wind stress curl that are believed to have caused the EAC to extend farther south over the past decade (Cai et al., 2005; Roemmich et al., 2007; Hill et al., 2011). Interestingly, in contrast to the EAC, there has been no significant trend in the EAuC transport over the past 30 years, and there is little correlation in variability with the large-scale or local wind forcing (Fernandez et al., 2018).

Improved estimates of the oceanic advection of heat in the EAC region would have a beneficial impact on weather forecasts, modeling of marine ecosystems, and fisheries management (Suthers et al., 2011). Transport estimates across PX30 show time-mean and low-frequency variability of the EAC transport that are consistent with overlapping and nearly collocated moored observations by Sloyan et al. (2016) (**Figure 7**). Studies

TABLE 1 | List of all currently operational XBT transects, with year of implementation, mode of operation, and main ocean properties they observe.

Transect	Start year	Current sampling mode	Main objectives
AX_WBTS	1995	HD/HR and FR	State and variability of the Florida Current
AX01	2000	HD/HR	North Atlantic subpolar gyre. Variability of MHT in the northern limb of the thermohaline circulation of the North Atlantic.
AX02	2008	HD/HR	Labrador Sea region, pathways and overflows of waters.
AX07	1994	HD/HR	MHT in the North Atlantic along ∼30°N, assessment of decadal variability in the North Atlantic Ocean. Variability of the Florida Current.
AX08	2000	HD/HR	Main zonal currents, countercurrents, and undercurrents in the tropical Atlantic Ocean. Gulf Stream. Atlantic subtropical gyres.
AX10	1996	HD/HR	Variability of location and transport of the Gulf Stream, their link to the NAO, sea level, and weather events.
AX18	2002	HD/HR	Meridional mass and heat transport in the South Atlantic and Brazil Current. Sometimes a somewhat northern transect that runs from Rio de Janeiro to Cape Town, referred to as AX17, is carried out.
AX22	1996	HD/HR	Interocean exchanges between South Atlantic and Pacific oceans, and Antarctica, Antarctic Circumpolar Current.
AX25	2005	HD/HR	Interocean exchanges between Indian Ocean and Atlantic Ocean waters, Antarctic Circumpolar Current.
AX32	2000	HD/HR	Monitoring of the Gulf Stream.
AX90	2013	HD/HR	Monitors the surface-to-bottom temperature of all water between Scotland and Iceland.
AX97	2004	HD/HR	Monitors the zonally integrated baroclinic transport of the Brazil Current and its associated mesoscale variability.
IX01	1983	FR	Indonesian Throughflow monitoring.
IX21	1994	HD/HR	Agulhas Current.
IX28	1992	HD/HR	Transports across the Southern Ocean in conjunction with AX25 and AX22.
MX04	2011	HD/HR	Variability of circulation of Tyrrhenian Sea
PX02	1983	FR	Indonesian Seas and the Indonesian Throughflow monitoring.
PX05	2009	HD/HR	East Australian Current, the low latitude boundary current in the Solomon Sea, and Kuroshio Current.
PX06/PX09/PX31	1986	HD/HR	Part of the Tasman Box (PX30,PX34,PX06). Sampling the East Auckland Current and the zonal tropical Pacific current system (PX06, PX09, and PX31).
PX11/IX22	1986	FR	Indonesian Throughflow, in regions of very shallow water and high currents.
PX30	1991	HD/HR	EAC boundary current regions. Part of the Tasman Box (PX30,PX34,PX06).
PX34	1991	HD/HR	Part of the Tasman Box (PX30,PX34,PX06).
PX37/PX37S	1991	HD/HR	California Current System.
PX38	1993	HD/HR	Subtropical/subpolar Pacific gyre.
PX40	1998	HD/HR	Kuroshio Current and interior subtropical gyre

that combine synergistic measurements of HD XBT data with altimetry and Argo observations are conducive to understanding the along-current variability of the EAC, resolving both the major jets and the EAC recirculation, and improving estimates of the basin-scale transports of mass, heat, and freshwater in the shallow South Pacific MOC. A pilot project that will merge data from the XBT network with multidisciplinary data from Argo floats, satellites, gliders, and ocean moorings is presently underway to connect ocean dynamics and productivity in the EAC and over the continental shelf.

Kuroshio Current

The Kuroshio Current, the WBC of the North Pacific gyre, is sampled by XBT transect PX40 (Honolulu to Yokohama) that began in 1998. This transect is often combined with XBT transects PX37 (San Francisco to Honolulu) and PX10 (Honolulu to Guam) to estimate the complete trans-basin mean heat and freshwater transports in the North Pacific (Uehara et al., 2008; Douglass et al., 2009, 2010; Auad et al., 2011; Nagano et al., 2012, 2016).

An analysis of the total heat budget of the North Pacific Ocean, including heat storage, air-sea flux, and heat transport by the ocean circulation, was carried out using HR XBT data and an ocean data assimilation model (Douglass et al., 2009, 2010). The mean offset between the northward heat transport from XBT data and that estimated from the model is due to the low model resolution near the WBC and to a meridional offset in the simulated position of the North Equatorial Current. Model-based and observational analyses show good agreement in their temporal variability, demonstrating large interannual variability in the ocean heat transport. The heat transport and heat storage components largely balance one another, with less variability in the air-sea exchange component.

Nagano et al. (2012, 2016) used the PX37/40 transect data to quantify the variability in the interior. Their integrated analysis of XBT, profiling float, and satellite altimetry data showed that

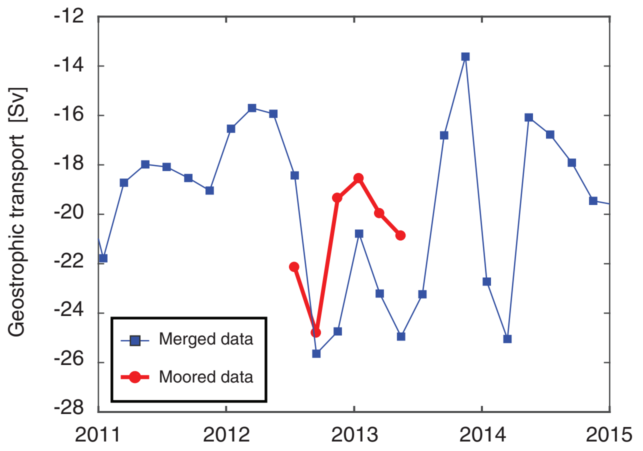

FIGURE 7 | Time series of the absolute geostrophic transport normal to the PX30 nominal track in the EAC region west of 155.3°E from 2011 to 2015, computed using merged high-resolution XBT (HR-XBT), satellite altimetry, and Argo profiles and trajectory data, are shown in blue. Transport estimates using moored data at 27°S are indicated in red. Both series are smoothed with a 4-month running mean. Transport estimates averaged between April 2012 and August 2013, are 23.3 Sv using the HR-XBT/Argo/altimetry method, and 21.1 Sv from moored data.

the volume transport-weighted temperature of the interior flow shows clear seasonality and that its anomaly from the mean seasonal cycle varies on quasi-decadal time scales. The weighted temperature peaked in 1998 and 2007, contributing between 6 and 10 TW to the net heat transport, ~1 year before peaks in SST occurred east of the Philippines. These results suggest that the heat budget of the warm water pool is sensitive to the interior heat transport in the central North Pacific. On interannual and longer time scales, the variability is mostly related to shifts in the Pacific Decadal Oscillation.

Indonesian Throughflow

One of the longest running transport measurements in the Indonesian region comes from the frequently repeated IX01 (Fremantle, Western Australia to Java) XBT section with approximately 18 repetitions per year since sampling began in 1983. Estimates of upper ocean temperature and geostrophic transport of the Indonesian Throughflow (ITF) therefore extend back 35 years (Sprintall et al., 2019). This remarkable XBT record confirms that the shallow ITF transport increases during La Niña and decreases during El Niño (Wijffels et al., 2008), but this effect is greatly weakened by canceling from in-phase wind forcing in the Indian Ocean associated with the IOD (Wijffels and Meyers, 2004; Liu et al., 2015). A clear long term strengthening of the ITF has been observed (Liu et al., 2015), likely associated with the strengthening Pacific Trade winds since 1984 (England et al., 2014).

Antarctic Circumpolar Current

In the Southern Ocean, westerly winds drive the flow of the ACC system and its associated fronts, serving as a major conduit for inter-oceanic exchange of heat and salt between the Pacific, Atlantic, and Indian oceans. There are three XBT transects that routinely monitor the ACC, strategically placed at inter-ocean chokepoints: AX22 (across the Drake Passage), AX25 (Cape Town to Antarctica), and IX28 (Hobart to Antarctica). One of the key contributions of these XBT transects in the ACC is an improved understanding of the underlying dynamics driving the multi-branch structure of the ACC, which largely determines the overall variability associated with this current (Sprintall, 2003; Swart et al., 2008; Sprintall et al., 2012; Domingues et al., 2014). These XBT sections also monitor the boundary currents, giving key seasonal and interannual observations of inter-ocean exchange (along the northern boundaries) and Antarctic boundary current variations (in the south).

XBT observations collected along AX25, when jointly analyzed with temperature and salinity climatological fields and nearby observations from Argo floats and satellite altimetry, show that the Subantarctic Front (SAF) and the Antarctic Polar Front transport together account for over 80% of the total ACC transport at this longitude (Swart et al., 2008). The year-to-year changes of frontal transports were driven by local winds associated with the Southern Annular Mode (Domingues et al., 2014). However, local winds were not directly linked to meridional excursions of these fronts in this region (Sallée et al., 2008). XBT data have shown that the location and transport of the various frontal regions along the AX25 transect do not have a strong annual cycle. The SAF transport, for example, is related to the local wind field and so exhibits a biannual period.

Observations along the northern part of IX28 south of Tasmania have revealed strong interannual variations in the exchange of subtropical waters from the Tasman Sea to the Indian Ocean that are linked to poleward shifts in the position of the Subtropical Front and the Subantarctic Front which are, in turn, impacted by El Niño-Southern Oscillation (ENSO) variability (Morrow et al., 2008; Sallée et al., 2008). Water mass variations here are strongly linked to mesoscale eddy activity from the Tasman Sea (Morrow and Kestenare, 2014; Pilo et al., 2015) and to cold-core eddies crossing the Subantarctic Front (Morrow et al., 2004).

In September 1996, a high-density XBT sampling program across the Drake Passage was initiated on the US Antarctic Program (USAP) vessel to study temperature and geostrophic transport variability: over 140 transects have been completed as of 2018. The AX22 transect represents the longest repeat year-round upper ocean transect in the Southern Ocean. In fact, the principal USAP vessel serves as a "super-ship" with concurrent measurements of near-surface currents and acoustic backscatter from shipboard acoustic Doppler Current Profilers (ADCP); salinity profiles obtained through Expendable CTD (XCTD) sampling; measurements of the near surface underway partial pressure of CO2 (pCO2) and discrete total CO2 (TCO2), nutrients, δ13C of TCO2, nutrients (nitrate, phosphate, silicate), and salinity. High-precision continuous atmospheric O2 and CO2 measurements were added in 2012. Typically, six to seven transects of XBT/XCTD and discrete surface measurements are completed annually, while the ADCP, pCO2, and atmospheric O2/CO2 sensors sample continuously along all cruise tracks, about 22 Drake Passage transects annually. Together these underway measurements provide concurrent information on the physical and biogeochemical air-sea variability at high temporal and spatial resolution on a near year-round basis, an unmatched achievement in the Southern Ocean.

The near-repeat HR XBT/XCTD/ADCP sampling along AX22 in the Drake Passage is designed to study modes of variability in the ACC on seasonal to interannual time scales (Sprintall, 2003, 2008) and on space scales from that of current cores (∼50–100 km) to eddies (∼10 km) (Lenn et al., 2007, 2011). The combined XBT temperature and ADCP velocity observations have been used to describe and quantify the mean jets, mesoscale variability, and eddy momentum and heat fluxes in the Drake Passage (Lenn et al., 2007, 2008, 2011; Firing et al., 2011) and to resolve the Southern Ocean Ekman layer (Lenn and Chereskin, 2009; Polton et al., 2013). These observations have also been used to determine variability in properties and fronts (Dong et al., 2006b; Thompson et al., 2007; Sprintall et al., 2012), and the mixed layer depth and shear (Stephenson et al., 2012, 2013; Brannigan et al., 2013). Additionally, the data have been used for validation of satellite products (Dong et al., 2006a, 2010). The combined observed nutrient, carbon, and XBT temperature AX22 time series were used to examine the balance of net community production in the surface layer, providing an opportunity to validate satellite-based productivity algorithms and to improve understanding of the role of the Southern Ocean in the global carbon cycle (Munro et al., 2015). Finally, the AX22 XBT data are also assimilated into the Southern Ocean State Estimate (SOSE) and used to test ocean and coupled climate models (Jiang et al., 2014).

XBT data have detected warming trends in the Southern Ocean and revealed details regarding processes that could lead to warming. In the Antarctic Zone, data from the IX28 and AX22 transects show that Antarctic Surface Water and Upper Circumpolar Deep Waters have warmed over the past several decades (Morrow et al., 2008; Sprintall, 2008) and that the cold Winter Water tongue has become warmer, thinner, and shallower. In the South African sector, warming anomalies observed using XBT data have reached values as large as 1°C in the Ekman layer that are linked with changes in the wind field that could potentially provide a source for the overall ACC warming. Large-scale changes in the wind forcing, related to the Southern Annular Mode, may contribute to the deeper warming trend in the vicinity of Antarctica (Morrow et al., 2008; Sprintall, 2008) and the periods of biannual fluctuations south of Australia (Morrow et al., 2008).

Mediterranean Sea

The MX04 XBT transect (Genoa to Palermo) has been sampling upper ocean variability in the Tyrrhenian Sea and the northeastern Ligurian Sea since September 1999. To date, about 90 transects have been completed, resulting in over 3,000 profiles. This XBT transect is nearly coincident with one altimetric track, allowing a combination of XBT, and remotely sensed sea surface height anomaly data to estimate the geostrophic circulation (Vignudelli et al., 2003; Ciuffardi et al., 2016; Napolitano et al., 2018). The Tyrrhenian Sea is an area where the mixing of the waters coming from the eastern and western Mediterranean occurs, while the formation of dense winter waters takes place in the Ligurian Sea. XBT temperature profiles have shown a warming that could be linked to the anomalous 2003 summer (an unusually long, hot, and dry season in the southern Europe). After a return to temperature conditions prior to 2004, a new anomaly appeared in 2014 in the Tyrrhenian Sea with a warming tendency in the 200–500 m depth layer moving from south to north (Ribotti et al., 2016). Over the years, this thermal anomaly has increased and extended both in depth (up to about 700 m) and in the involved areas, which include the northeastern part of the Ligurian Sea (albeit with lower intensity). Even if in a non-homogeneous way, this heating process continued until the end of 2018, when the warming seems to have stopped. The current temperature variations with respect to the pre-warming conditions are in the range of 0.3–0.6°C and decrease when latitude and depth increase. The mechanism producing these recent anomalies is still under analysis because it is unclear whether it can be explained in terms of climatic changes or variability of circulation (Schroeder et al., 2017; Von Schuckmann et al., 2018). The warming of seawater in the Ligurian and Tyrrhenian seas also appears to be connected to a recent increase in local extreme weather events. The monitoring of these two seas is thus crucial for a correct interpretation of the ocean-atmospheric variability, and the MX04 XBT transect is able to easily provide very useful data for such analyses.

Meridional Heat Transport

Meridional Heat Transport in the Atlantic Ocean

In the Atlantic, zonal XBT transects AX18 and AX07 are used to assess the Atlantic MHT and the AMOC at 35°S and 30°N, respectively. Although mooring arrays have been in place since 2004 in the North Atlantic and 2009 in the South Atlantic to observe and monitor the AMOC (Frajka-Williams et al., 2019), deriving MHT from these boundary arrays is challenging without temperature measurements in the interior region.

The AX18 XBT transect with trans-basin temperature measurements is the only observing system currently available to provide MHT estimates in the South Atlantic. Results obtained to date from AX18 show that the MOC and MHT across 35°S are approximately 18.47 ± 1.73 Sv and 0.56 ± 0.13 PW, respectively, and have not experienced statistically significant trends during the observing period. A distinguishable seasonal cycle was, however, found for the geostrophic and Ekman heat transports, which have similar amplitudes but are close to 180° out-of-phase. Consequently, this explains the small amplitude of the seasonal cycle in the total northward MHT and MOC (Dong et al., 2009, 2011). Statistical analyses of the MOC and MHT in this region using XBT data indicate that they are significantly correlated. Results from this transect also provide a ground truth for evaluating numerical models and methodologies to estimate the MOC using other data sources. Current generation climate models are unable to reproduce the seasonal variations in the geostrophic transports; subsequently, the model MOC and MHT seasonal evolution is controlled largely by Ekman transport (Dong et al., 2014). A detailed analysis of XBT observations show that the weak seasonal cycle in geostrophic transport from Coupled Model Intercomparison Project Phase 5 (CMIP5) Models [National Center for Atmospheric Research Community Climate System Model (NCAR-CCSM4) and the Geophysical Fluid Dynamics Laboratory Earth System Model (GFDL-ESM2M)] is due to poor representation of the boundary currents and vertical stratification.

Some XBT transects are currently being assessed using Observing System Experiments (OSEs) to determine the best strategy for monitoring currents and mass and heat transports. For example, AX18 was assessed using the HYbrid Coordinate Ocean Model (HYCOM)/Navy Coupled Ocean Data Assimilation (NCODA) eddy resolving analysis (Goes et al., 2015a). Results showed that horizontal resolution finer than 25 km is required to resolve boundary currents, that at least 15 years of quarterly sampling is needed to resolve the seasonal cycle of the MOC, and that altimetric sea level height can be used to infer the barotropic mode.

The close relationship between satellite sea surface height anomalies with the vertical temperature structure between 20° and 34.5°S (Dong et al., 2015) has allowed the assessment of changes in MOC/MHT with latitude back to 1993, the start of operational satellite altimetry observations. The 20-year time series of the altimetry-derived MOC showed the geostrophic component dominant during the 1993–2006 period and the Ekman component dominant between 2006 and 2011 at 34.5°S (Dong et al., 2015). One important result is that during 2017 the MHT at latitudes between 20° and 34.5°S show strong positive anomalies (**Figure 8**), which were dominated by the geostrophic transport at 20° and 25°S and by the Ekman transport at 30° and 34.5°S[3]. This indicates that measurements of both the water column density and surface wind fields are needed to correctly assess the MHT. The multi-latitude estimates of the MOC and their co-variability with SST further allowed development of MOC indices back to the 1870s using SST reanalysis products (Lopez et al., 2017). The century-long MOC indices were used to investigate the link between the South Atlantic MOC and changes in climate and extreme weather events, as suggested by climate models (see section Regional sea level changes).

In the North Atlantic, ongoing analyses of observations along AX07 have shown that the 20-year mean MHT at 30°N is about 1.16 ± 0.19 PW, largely due to geostrophic transport (1.13 ± 0.25 PW) and that the temporal variability of the MHT is highly correlated with the geostrophic component ($R = 0.90$)[4]. The correlation between MHT and its Ekman component is somewhat lower and negative (−0.33), but still exceeds the 95% significance level of 0.22. In contrast to that in the South Atlantic, the MHT and its geostrophic component at 30°N do not show a significant seasonal cycle, although the Ekman component varies seasonally with high values during winter and low values during summer. The 20-year time series from AX07 suggests an increasing trend of 0.21 ± 0.07 PW/decade in the geostrophic transport, which is partially compensated for by the decreasing trend of 0.11 ± 0.03 PW/decade in the Ekman transport. An analysis of XBT observations finds that the total MHT across 30°N has a net increasing trend of 0.10 ± 0.06 PW/decade.

Frajka-Williams et al. (2019) provides a discussion of the different approaches for estimating the AMOC, including their advantages and limitations. They also provide key results when using the various observational platforms and make suggestions for implementing future observational efforts.

Global and Regional Ocean Heat Content

XBTs have provided about 38% of the global temperature observations obtained between 1970 and 2000 for profiles down to a depth of 300 m and a larger portion for profiles to 700 m depth. During the Argo era, ∼15% of the global temperature profiles are still from XBT deployments. As such, XBT observations have been, and continue to be, an essential source of information for the derivation of global and regional OHC changes since the 1970s (Lyman et al., 2010; Abraham et al., 2013; Boyer et al., 2016; Cheng et al., 2016b, 2017). As assessed by the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC-AR5) (Rhein et al., 2013) and other studies (Domingues et al., 2008; Lyman and Johnson, 2008; Cheng et al., 2017), uncertainty in global OHC is reduced after ∼1970, coincident with improved sampling due to the introduction of the XBT network (to 400 m depth). With this long-term accumulation of XBT data, scientists can now provide a long-term record for OHC change as a basis for mapping ocean heat uptake (**Figure 9**). Since OceanObs'09, Levitus et al. (2012) and Ishii et al. (2017) have provided major updates to their long-term OHC estimates since the 1950s. Recently, Cheng et al. (2017) proposed an improved estimate of OHC, since 1960, using a recommended XBT data quality improvement scheme (section Technological Improvements). All of these estimates show a significant ocean warming since 1960, with an acceleration since the 1990s (Wijffels et al., 2008; Gleckler et al., 2016; Cheng et al., 2017). All major ocean basins have experienced significant warming since 1960, with the greatest warming in the southern oceans south of 30°S (Cheng et al., 2017) (**Figure 9**). The significant Southern Ocean warming is mainly due to the increased greenhouse gas effect (Shi et al., 2018; Swart et al., 2018). Decadal and multi-decadal scale OHC changes in the Indian Ocean were also robustly observed and are due to the changing relative contribution of Pacific wind forcing through the ITF, local wind, and heat flux forcing over time (Lee et al., 2015; Nieves et al., 2015; Li et al., 2018).

The observed long-term OHC record also provides a key tool to evaluate climate models. Cheng et al. (2016a) and Gleckler et al. (2016) compared the observed OHC records with simulations from CMIP5 during the 1970–2005 period, showing that the CMIP5 ensemble mean agreed with observations, although an underestimation of the global ocean warming in the Southern Hemisphere could be possible due to poor sampling (Durack et al., 2014). However, the uncertainties in models are much larger than in the observations, indicating that observational OHC records, including those that use XBT observations, remain a critical metric for model evaluation.

The subsurface temperature data in the western North Atlantic Ocean can be used to investigate variations in the

[3] www.aoml.noaa.gov/phod/indexes/samoc_alt.php

[4] www.aoml.noaa.gov/phod/soto/mht/ax7/report.php

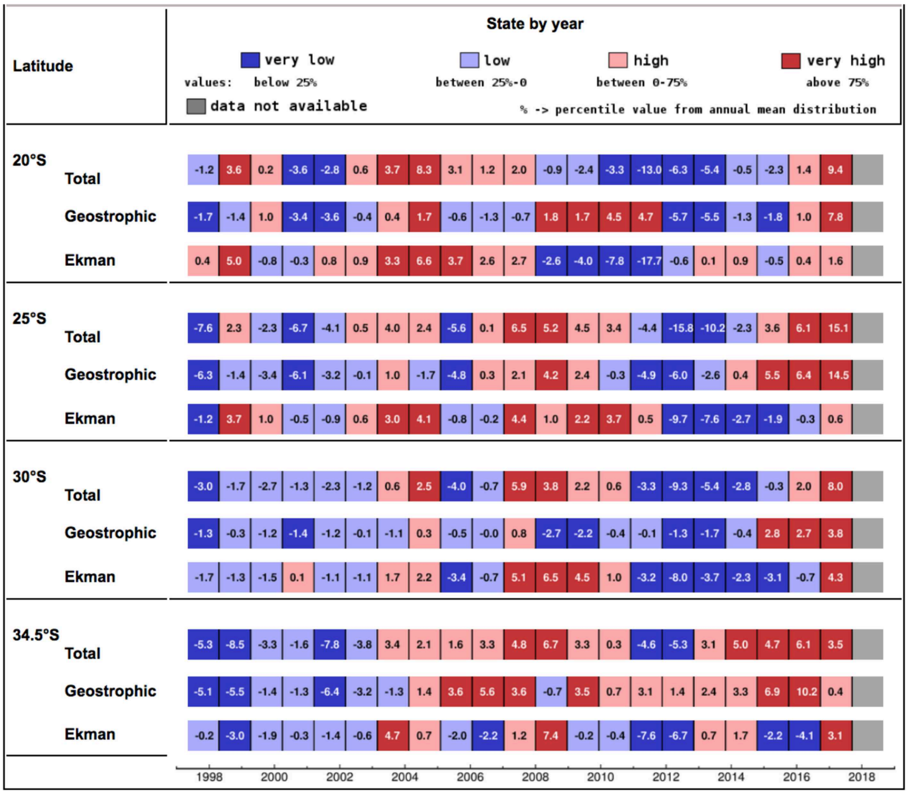

FIGURE 8 | Meridional Heat Transport (MHT) anomalies in the South Atlantic using a combination of XBT, satellite altimetry, and historical hydrographic observations with the red (blue) colors indicating values higher (lower) than the 1993–2017 assessment period average. Values are reported in Petawatts (1 PW = 10^{15} watts), and multiplied by 100 for display purposes.

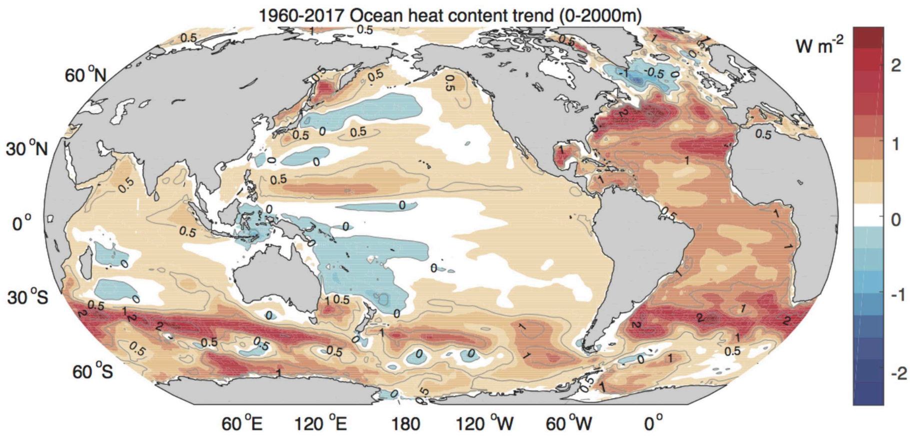

FIGURE 9 | Observed ocean warming rate in the upper 2000 m since 1960 (Figure updated from Cheng and Zhu, 2016 and Cheng et al., 2017). The data used to generate this figure is from gridded ocean temperature analysis in Cheng et al. (2017), and this analysis is based on all available *in situ* ocean subsurface temperature observations (including XBT data) from World Ocean Database (Boyer et al., 2013).

upper OHC and to assess the contributions from surface heat fluxes and oceanic processes (Dong et al., 2007a). A heat budget study in a region bounded by the XBT transects AX07, AX08, AX10, and the Gulf Stream (Dong et al., 2007b) indicates that the year-to-year upper OHC changes were driven by the oceanic heat transport, which was dominated by the geostrophic component. The heat content anomalies, in turn, forced anomalous air-sea heat exchanges, suggesting that geostrophic advection in the Gulf Stream plays an important role in air–sea coupling.

Operational Oceanography and Ocean Forecasts

In the context of operational oceanography, XBTs are widely used among international centers that run Ocean Forecasting Systems (OFSs). Tonani et al. (2015), in a revision of the status and future of global and regional ocean prediction systems, provided a geographic distribution of the centers that developed OFSs under the Global Ocean Data Assimilation Experiment (GODAE) and GODAE OceanView initiatives. The configuration of OFSs is quite variable in terms of horizontal and vertical resolution, the base model adopted, and data assimilation. While some of the systems are limited to a specific geographic region (e.g., the Oceanographic Modeling and Observation Network, REMO configuration focuses only on the South Atlantic Ocean), 12 of these OFSs are global systems. A common ground for these systems is the use of vertical profiles of temperature and salinity from different platforms (e.g., ship-based CTD, XBT, Argo, gliders, and drifters) in their data assimilation schemes. Martin et al. (2015) presented a more detailed description of seven of these systems, which assimilate XBT data in near real-time.

In terms of representativeness and impact, vertical profiles of temperature that are obtained from different observational platforms are being evaluated in a complementary manner. In an assessment of the current status of the real-time *in situ* GOOS for operational oceanography, Legler et al. (2015) argued that XBT transects provide a very different view of the global ocean to that of Argo floats. XBT deployments sample along well-observed transects, at either large or small spatial scales or at special locations such as boundary currents and chokepoints, all of which are complementary to the global Argo broad scale array.

The impact of XBT data on improving OFSs can be assessed by OSEs. In a near real-time OSE using the UK Met Office's operational OFSs–Forecasting Ocean Assimilation Model where XBT data were not assimilated, Oke et al. (2015a) found that although XBT data did not significantly impact global metrics, they did have significant local impacts. On a global scale, suppression of XBT data resulted in a mean (maximum) temperature difference of ∼0.04°C (5.42°C), which compares to a difference of 0.27°C (10.53°C) in the case of suppressing Argo data. Moreover, Oke et al. (2015a) argued that, although XBT data represented a small component of the GOOS, their impact in the vicinity of the XBT transects was significant. Suppression of XBT data resulted in a marked degradation of the forecast system. Focusing on regional applications, Oke et al. (2015b) found that carefully designed *in-situ* observation arrays (e.g., optimized glider fleets and XBT observations) added significant constraint to high-resolution models, with improvements as much as 40% in the representation of ocean density (Oke et al., 2015b).

Reanalysis Products

Estimation of the tropical ocean's state is important for seasonal to interannual predictability. For example, ocean observing systems in the tropical Pacific are frequently evaluated by carrying out estimates of ocean state ("reanalysis") and comparing them to withheld observations. Errors in reanalysis products include both formal mapping errors arising from sparse or noisy observations and representation errors that arise from low resolution, missing physics, or errors in the model–data synthesis methodology.

The evolution of the Tropical Pacific Observing System (TPOS) 2020 project recommends the use of data assimilation to combine observations and to assess the design of the TPOS. A necessary first step in this procedure is to have a measure of the errors and performance of the assimilation systems. Verdy et al. (2017) evaluated the performance of a 4-Dimensional Variable system that assimilates Pacific Ocean XBT transect data, as well as Argo and remotely-sensed sea surface height (SSH) data sets, as a necessary step to inform use of the output for dynamical analysis or for data impact studies. A comparison to independent observations from Tropical Atmosphere Ocean (TAO) moorings showed that for time scales shorter than 100 days the state estimate that included the Pacific XBT data improved estimates of TAO temperature relative to an optimally interpolated Argo product. The improvement was greater at time scales shorter than 20 days.

SOCIETAL BENEFITS OF XBT OBSERVATIONS

Extreme Weather

The time series of MHT in the South Atlantic, obtained using a combination of XBT and satellite observations and coupled general circulation models, has served to assess the potential predictability of monsoon rainfall. The global monsoon system is defined by regions where summer precipitation exceeds 75% of the total annual rainfall (Wang et al., 2012). These regions encompass more than 55% of the global population and are important sites for global agricultural output. Decadal variability of the South Atlantic MOC and MHT plays a key role in modulating global atmospheric circulation via its influence on interhemispheric redistributions of momentum, heat, and moisture that influence the global monsoon system (Lopez et al., 2016). MOC variability could modulate the strength of global monsoons with a 20–30 year advance lead time (Lopez et al., 2016), which suggests that the time series obtained from the AX18 XBT transect at 34°S could serve as a predictor of monsoon precipitation.

Transport estimates from the AX18 transect were used to reconstruct a century-long MOC estimate from 20° to 35°S in the South Atlantic (Lopez et al., 2017) using a multivariate Empirical Orthogonal Function method, which quantifies the joint covariability between MOC and SST (**Figure 10A**). Four SST products were employed, including the Hadley Center SST (HadSST), the Extended Reconstructed SST version 3 and 4 (ERSSTv3 and ERSSTv4), and the Centennial Observational Based Estimates SST (COBE-SST). An MOC was jointly derived from XBT and altimetry observations that extend from 1993 to the present (2017). For reconstruction purposes, this is referred to as the training period to obtain the joint covariance of observed SST-MOC. The reconstructed century-long MOC was then used to assess the role of the MOC in modulating extreme weather events, such as heat waves over the US (**Figure 10B**). For example, there is an increase in the likelihood of heat

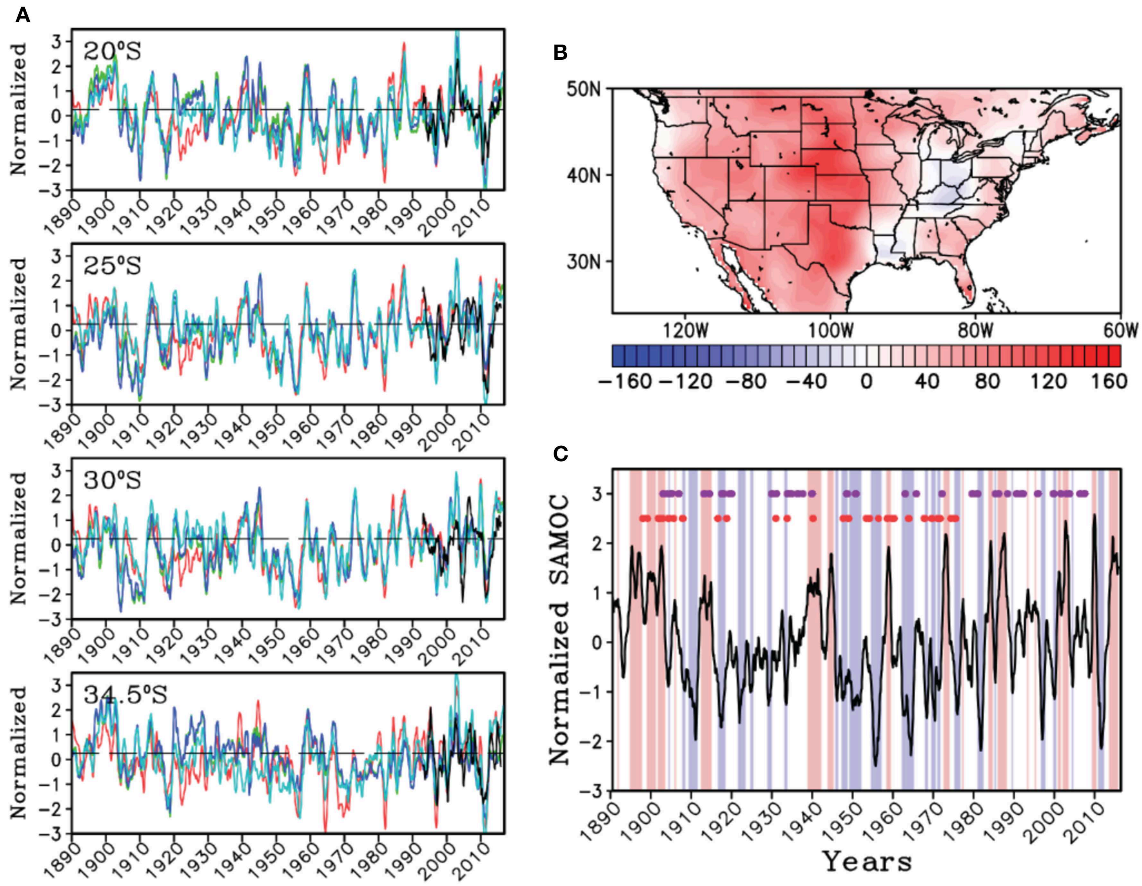

FIGURE 10 | (A) Reconstructed South Atlantic MOC at four different latitudes from 1870 using XBT, satellite altimetry observations (black), and SST from HadSST(red), ERSSTv4 (green), ERSSTv3 (blue), and COBE-SST (cyan). **(B)** Percentage change in the number of heat waves during weak minus strong South Atlantic MOC when the MOC leads heat waves by 30 years. **(C)** Reconstructed South Atlantic MOC from HadSST at 30°S (black) with periods of strong (weak) MOC red (blue) shading. The historical US heat waves are shown by the purple dots (red dots are lagged by 30 years to show the correspondence of weak MOC and more heat wave events 30 years later).

waves in the US when the South Atlantic MOC is weaker than normal compared to those periods when the MOC is stronger than normal. South Atlantic MOC variability leads US heat wave occurrence by about 30 years (**Figure 10C**). This is consistent with the model results of Lopez et al. (2016) and highlights the need for continuing the effort to monitor the MOC through XBT and other observational platforms, as the MOC is a potential predictor of high-impact extreme weather events on decadal timescales. This longer time series, together with historical weather records, will allow us to dynamically and statistically assess the role of the South Atlantic MOC on global weather events.

Regional Sea Level Changes

Coastal sea level changes are caused by the combined effect of various global and regional forcing mechanisms. Along the US East Coast, changes in the Florida Current and Gulf Stream dynamics and heat content are one source of sea level variability. During 2010–2015, accelerated sea level rise with rates as large as 25 mm year^{-1}, five times larger than the global average for this period, were observed along the southeast US coast that coincided with extensive flooding of large urban areas such as Miami, Florida. Simultaneously, sea levels decreased rapidly north of Cape Hatteras at similar rates (Domingues et al., 2018).

Over 2,000 XBT temperature profiles from transects AXWBTS and AX07, used together with ship CTD data, allowed for the identification of a temperature shift of the Florida Current from a cold phase (2010–2013) to a warm phase (2014–2015). Altimetry and tide gauge data showed that the warm phase caused the accelerated sea level rise recorded between Key West and Cape Hatteras (red line, **Figure 11**). The Florida Current warming recorded during this period accounted for ∼13 cm of sea level rise solely due to a thermal expansion of the water column (magenta line, **Figure 11**). A continuous record of the Florida Current transport in the Florida Straits further indicated that the transport remained relatively constant during this time period (filled curve, **Figure 11**), revealing the dominant contribution of temperature changes for driving coastal sea level changes (Domingues et al., 2018).

North of Cape Hatteras, more than 10,000 XBT observations from transects AX10, AX08, and AX32 revealed that the observed sea level decline along the coast coincided with a cooling of the water column over the shelf (not shown). Sea level decline in this area was largely accounted for by an increase in atmospheric pressure combined with a small contribution from cooling of the water column over the continental shelf (Domingues et al., 2018). Sustained XBT observations allowed for the identification of key changes in these boundary currents that contributed to coastal flooding events affecting highly populated urban areas.

DATA MANAGEMENT

Data Transmission

XBT profiles are generally transmitted from ship to shore using satellite communications networks (e.g., Iridium, Argos, Inmarsat). When near real-time transmission is not possible, the profiles are sent to transect operators once the ship arrives in port. Each profile undergoes a quality control (QC) process in which a series of tests assesses the overall quality of the measurements. Some data centers apply initial automatic procedures; profiles that fail these tests move to a visual QC (VQC) stage. Other data centers proceed directly to the VQC stage. In VQC, the profiles are visually inspected and quality flags are applied. The QC tests check for the presence of spikes, constant value profiles, extreme depth, and temperature values, impossible dates and locations, vertical gradients and inversions, wire breaks, seafloor contact, etc. (Bailey et al., 1994; Thadathil et al., 2001). Once the profile QC phase is complete, all profiles approved during this process are encoded into FM 63-XI Ext. BATHY (the traditional alphanumeric code for reporting temperature profiles) and/or BUFR (Binary Universal Form for the Representation of meteorological data) bulletins and submitted to the GTS for worldwide distribution in near real-time. The GTS is a core component of WMO's World Weather Watch Programme and contributes to the rapid collection and distribution of satellite, *in situ*, and other processed datasets (WMO, 2015b).

The collection and distribution of XBT data is routinely performed through GTS centers in the United States, Australia, Japan, France, Canada, and Brazil. The centers in the first four countries also disseminate the profile data and associated metadata in BUFR format. BATHY encoded GTS distributions are gradually being discontinued within the XBT community, in accordance with the WMO mandate to fully migrate to BUFR. The reasons behind this decision are based on the development of new and dynamic requirements, a higher volume and complexity of data and metadata, a promotion of automation, and the limitations of the traditional fixed alphanumeric codes such as BATHY, which restrict the number of metadata fields and do not include QC flags. In BUFR, XBT profiles are encoded into the operational common sequence 315004, which incorporates all of the common metadata fields, as well as full resolution data (WMO, 2015a).

Data tracking activities include the collection of XBT BATHY and BUFR reports arriving from the GTS. Monitoring the different stages of the data management process serves to generate reports, detect anomalies and data gaps, and analyze the performance and latency of the data collection and distribution system. The data originators retain the original and delayed-mode QC profiles and intermediate products.

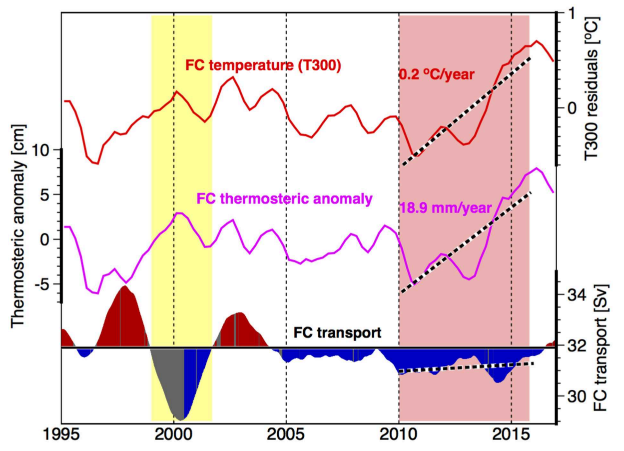

FIGURE 11 | Time-series of the average temperature residuals (seasonal cycle removed) for the upper 300 m of the water column in the Florida Straits (red, T300), of thermosteric anomalies derived from the temperature data observed in the Florida Straits (magenta), and of the Florida Current (FC) volume transport (red and blue filled curve) measured in the Florida Straits using telephone cable voltage differences, and complemented using satellite altimetry data (gray). All time series are displayed after applying a 1-year low pass filter.

XBT data posted to the GTS in near real-time are collected by the Marine Environmental Data Section (MEDS) of the Oceans Science Branch, Fisheries and Oceans in Canada, along with other ocean temperature profile data, and relayed as a package every 3 days to the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information (NCEI) in the US. NCEI hosts the long-term archive center of GTSPP and preserves XBT data in the GTSPP Continuously Maintained Database (CMD). The delayed-mode profiles (those that are either not posted to the GTS or are full resolution or are fully quality controlled replacements for the GTS versions) are sent to NOAA/NCEI for inclusion in the GTSPP, from where they are disseminated and enter other global data sets such as the NOAA/World Ocean Database, thus becoming part of the data flow of the JCOMM Marine Climate Data System. Every other year, the data centers and XBT providers gather under the auspices of GTSPP to discuss potential improvements to quality control and global dissemination of XBT data.

Data Quality

Decades of effort have been made by the XBT community to improve XBT data quality (e.g., Hanawa et al., 1995), and significant progress has been achieved in data quality improvements since OceanObs'09. More tools and methods are now being used to better understand the accuracy of

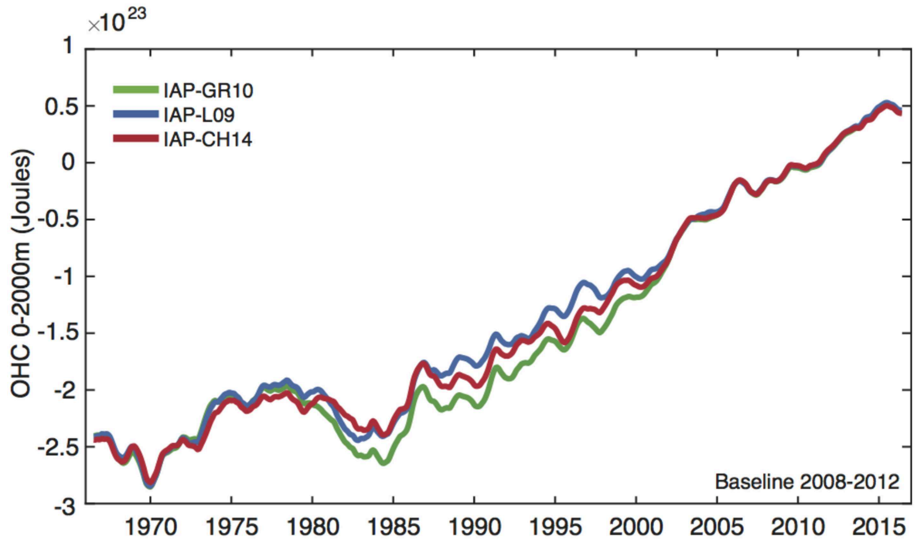

FIGURE 12 | Global OHC time series in the upper 2000 m after applying three XBT data improvement schemes: Levitus et al. (2009)-L09 (blue); Gouretski and Reseghetti (2010)-GR10 (green); and Cheng et al. (2014)-CH14 (red) based on the mapping method proposed by the Chinese Institute of Atmospheric Physics (IAP) in Cheng and Zhu (2016).

XBT fall rates and temperature measurements. These tools include traditional side-by-side XBT and CTD comparisons (e.g., Thadathil et al., 2002; Hamon et al., 2012; Cowley et al., 2013; Cheng et al., 2018), tests in swimming pools and water tanks (e.g., Bringas and Goni, 2015), Geophysical Fluid Dynamics models (Abraham et al., 2012, 2014; Gorman et al., 2014; Shepard et al., 2014), comparison with Argo and satellite altimetry data (DiNezio and Goni, 2010), and temporal changes of biases (DiNezio and Goni, 2011; Good, 2011; Gouretski, 2012). A careful analysis of the different individual probe types is in progress (Reseghetti et al., 2018), as different probe types have different characteristics in probe design that may impact data quality. An overview of the progress made in improving data quality can be found in Cheng et al. (2016b).

In 2016, the XBT science community recommended the use of an XBT data improvement scheme based on the bias corrections (Cheng et al., 2014, 2016b). The new XBT scheme allows for improved XBT observations in the estimates of global OHC. Using the three XBT data performance methods (Levitus et al., 2009; Gouretski and Reseghetti, 2010; Cheng et al., 2014) results in near-identical global OHC changes in the upper 2000 m since 1966 based on the mapping method proposed in Cheng and Zhu (2016) (**Figure 12**). In addition, temporal, and spatial variability of locations and transports of ocean currents, estimates of MHT and MOC, and the determination of mixed layer depths are robust for any XBT data improvement scheme (Goes et al., 2015b; Houpert et al., 2015).

TECHNOLOGICAL IMPROVEMENTS

XBT Probes

Based on theoretical and observational experiments, improvements have been proposed to the accuracy of both the XBT depth estimate and the measured temperature. To improve estimates of probe depth, the addition of pressure switches has been proposed. Pressure switches are small resistors that are activated at certain depths during the probe descent, marking those depths in the profile with spikes. These spikes are filtered during post processing, and their depths are recorded and used to correct the derived-depth estimates of the full profile. In a theoretical study, Goes et al. (2013b) showed that one pressure switch can limit depth errors from 2% of depth to ∼3.5 m. The implementation of pressure switches may increase the cost of XBT probes, an issue that will be jointly assessed by the manufacturer and the scientific and operational communities. The probe-to-probe variability of the linear depth bias might also be reduced by using a tighter weight tolerance of the probes. At present, the stated weight tolerance of Deep Blue probes, the most widely used probes, is ±2.5 g (±1 g for the metal head and ±1.5 g for the wire). However, reducing the tolerance to ±1.1 g in a sea trial did not produce significant improvements (Goes et al., 2017). Additional tests are needed to assess the importance of tighter weight tolerance on probe linear biases to confirm the results of theoretical assessments (Green, 1984; Abraham et al., 2012).

The temperature accuracy of XBTs stated by the manufacturer (Lockheed Martin Sippican, Inc.) is 0.2°C. Changes in probe specifications and acquisition systems can impact this accuracy. Goes et al. (2017) found that thermistor calibration, performed in a strictly controlled temperature bath, can improve XBT accuracy to 0.03°C at practically no additional cost.

XBT Launcher Systems

Many advances have been made over the years in collecting and distributing XBT data more effectively. Initially, XBT probes were deployed by a trained operator using a hand-launching system. On many projects, it is necessary to deploy XBTs on a 24-h-a-day schedule as the ship steams along its course. To reduce the workload and personnel, an XBT probe autolauncher was developed that allowed this work to be performed by one person. New autolaunchers can be preloaded with a number of probes (6–12) that are then deployed at predetermined launch times or positions. Autolaunchers have been developed by several institutions, including NOAA, Scripps Institution of Oceanography, CSIRO, and the University of Rhode Island. For example, a recently developed Automated eXpendable Instrument System (AXIS; Fratantoni et al., 2017) in 2012, enabled XBT sampling across an entire section from the continental shelf to Bermuda without the need for an observer on board. Autolaunchers are mounted to the stern of the ship and cabled to a room, where they interface with the data acquisition computer. The length of the cable-run can vary from ship to ship but is on average >75 m. Laying the cable alongside the ship can be difficult and time-consuming because of the limited amount of deck space available for installation. To alleviate the installation and break-down of the current setup, a power independent, wireless autolauncher using a standard wireless access point, a battery, a solar panel, and other off-the-shelf equipment and software tools, has been developed as a "cable replacement" for the standard XBT autolauncher system (Fratantoni et al., 2017). The improved setup will consist of Wifi technology coupled with a remote desktop client that in theory can be operated using only a tablet computer from within the vessel or operated from a land-based station via the Iridium satellite network.

Data Acquisition and Transmission Systems

The data acquisition recorder is the backbone for collecting accurate XBT data. A new XBT prototype data recorder is currently being tested to improve the number of data dropouts in the transmissions and to reduce the cost of servicing and upgrading existing data acquisition systems. These measures may reduce hardware costs by 85%.

Historically, the real-time transmission of XBT data had been mostly carried out using the Inmarsat-C satellite system. With the development of a more cost-effective, Iridium-based transmission system, the average transmission cost per XBT profile was reduced by 95% per profile during the last 10 years since Ocean Obs'09. Although originally developed to be used for XBT observations, these transmission systems have also been expanded to transmit other types of data, such as thermosalinograph (TSG), pCO_2, and marine weather observations.

THE FUTURE OF THE GLOBAL XBT NETWORK

Twenty years after OceanObs'99, the Global XBT Network continues to increase in value, not only through the growing length of the decadal time-series along individual transects, but also due to integrative relationships with other elements of the ocean observing system. Uniquely, the Global XBT Network provides spatial and temporal sampling that cannot as yet be reproduced by other existing platforms. One of the key strengths of the network is that XBTs have low operational costs and can be readily deployed on a repeat basis with varying spatial resolution. It is expected that the Global XBT Network will remain active and be enhanced over the next 10 years. We conclude with a list of key aspects that the scientific community has determined to be important for future studies involving XBT observations.

- **Sampling strategies.** One unique quality of XBT observations is their ability to sample along fixed trans-basin transects and across boundary currents in a sustained fashion, which presently cannot be reproduced by any other platform. Other components of the ocean observing system (e.g., profiling floats, gliders, moorings, etc.) provide complementary profiles of ocean temperature and other properties in these regions; however, none can replicate the rapidly-occupied transects in nearly repeated locations that have been obtained by XBTs for decades.
- **Maintenance of long climate record.** Several of the time series initiated and still maintained by XBTs have been in place for 30 years or longer. During the next decade, XBTs are likely to remain an integral part of the coordinated observing effort that continues collecting key oceanic temperature measurements for monitoring boundary currents (section Ocean currents, gyres, and ocean variability), MHT estimates across ocean basins (section Meridional Heat Transport), and global OHC assessments (section Global and regional ocean heat content).
- **Improvement of data quality.** As with other observing platforms, experiments and studies will continue to be carried out to improve the quality of XBT observations. This will be addressed by continuing to reduce errors in each subgroup of XBT data (i.e., data of the same probe type, data from the same year, etc.) (section Technological Improvements) and by improving probe design to increase the precision of each individual measurement (section The future of the Global XBT Network). The continuous improvement of XBT data quality justifies the merging of XBT data with data from other platforms (i.e., Argo, CTD), allowing for better monitoring and analysis of climate change and variability (i.e., section Global and regional ocean heat content).
- **Meridional heat transport.** The Global XBT Network continues to provide key assessments of oceanic temperature profiles at different latitudes, particularly in the North Pacific and South Atlantic oceans to monitor the current state of the MOC and associated MHT. These data will contribute to studies that link trans-basin heat transports with atmospheric circulation that may influence regional and global climate and extreme weather, aiding in the development of forecasts and outlooks of high-impact extreme weather events.
- **Simultaneous meteorological and oceanographic observations.** Meteorological sensors can be easily integrated into existing XBT transects to provide key meteorological data collected simultaneously with upper ocean thermal observations to calculate surface heat and moisture fluxes, which are critical for weather and climate research. Other

instrumentation that can be installed on ships of opportunity include pCO2 systems, continuous plankton recorders, acoustic current Doppler profilers, etc.

- **Sea level change.** Studies of sea level change attributions, such as that being performed off the US East Coast (Domingues et al., 2018), serve as examples for similar studies that may be conducted outside coastal areas where XBT observations continue to provide long-time series of variability of ocean currents, such as the Brazil Current. Ocean observations, including those from XBTs in these coastal areas, are critical for the continuous understanding and monitoring of key drivers of disruptive, and oftentimes destructive, flooding events due to elevated sea levels.
- **Submesoscale Ocean Dynamics.** Of current interest in oceanography is the monitoring of submesoscale features and processes (<10 km) across strong boundary currents, mesoscale eddies, and meanders. The XBT network can contribute to this effort in coordination with semi-Lagrangian observing platforms, such as underwater gliders and drifters. For example, the challenges that gliders may encounter while measuring across strong currents could be avoided by increasing the spatial sampling along selected portions of XBT transects.
- **Internal tides.** As we move to finer-resolution altimetric observations, with along track Synthetic Aperture Radar (SAR) missions (e.g., Sentinel-3) and the future Surface Water and Ocean Topography (SWOT) 2D missions, these long time series of XBT observations are being reassessed. High-frequency internal tide variability was historically filtered out of XBT data to concentrate on the larger-scale eddies and circulation. Now that altimetry is capable of observing the sea level variations of these signals, there are opportunities for data mining of the older XBT data to help validate the altimetric internal tide observations, as well as ocean models including internal tides. Future XBT or glider observations along SAR-altimetry or SWOT tracks will provide invaluable vertical structure to help interpret these dynamical processes.
- **High northern latitude observations.** The existing XBT transects AX01 (Greenland to Denmark) and AX90 (Iceland to Faroe Island to Shetland Islands) in the subpolar North Atlantic have provided valuable information on meridional volume and heat transports (e.g., Rossby et al., 2018). There is future potential to significantly enhance the present-day observing system in the high latitudes by establishing a new XBT transect between continental Norway and Svalbard. Possible instrumentation of a Norwegian supply vessel with a shipboard ADCP and an XBT launcher would provide accurate measurements of ocean currents and temperature fluxes across this most important Arctic gateway at high spatial and temporal resolution. This will result in improved monitoring of oceanic fluxes into the Arctic Ocean, a region experiencing dramatic climate change.
- **Observing system experiments and observing system simulation experiments.** Both OSEs and Observing System Simulation Experiments (OSSEs) are needed to carry out quantitative evaluations of the impact of ocean observations, including XBTs. OSEs serve to assess the impact of actual observations on ocean forecasts or reanalyses, while OSSEs provide a rigorous approach to evaluate the potential impact of new observing systems or to improve the sampling of current observations. With the implementation of new observing platforms it is necessary to quantitatively assess the complementary value of a suite of temperature profiles at different spatial and temporal scales for a range of studies.
- **A platform to deploy other observing instruments.** Vessels involved in the work of the SOT, and particularly in the XBT network, often also support other networks, e.g., through the deployment of autonomous instruments (drifters, floats) or installation of underway systems (e.g., TSGs). Coordination and monitoring of ship contributions across all observing networks is of growing importance, not only for a better exploitation of synergies (e.g., maintenance and logistics), but also for not overburdening ships with too many tasks for a variety of purposes. JCOMMOPS[5] has developed online tools that will allow for a centralized and harmonized registration of cruises, instruments, and deployment plans, all referring to a commonly used ship reference list with unique identifiers.
- **Hurricane applications.** A potential application for XBTs is to improve seasonal hurricane outlooks. In the Pacific Ocean, PX09 (Honolulu to Suva)/PX31 (Los Angeles to Suva) and PX40 data are used to derive OHC estimates to improve tropical cyclone intensity forecasts (Shay and Brewster, 2010; McCaskill et al., 2016). The AX08 transect crosses the development region for Atlantic hurricanes, a region where coupled models generally present a cold bias and where cyclone development is affected by eddy, interannual, and decadal upper OHC variability via turbulent heat fluxes. The use of AX08 data to assess and improve ocean models has the potential to also improve seasonal outlooks and/or intensification forecasts of Atlantic hurricanes (Domingues et al., 2019).
- Redundancy of observations. Finally, it is important to recognize that some redundancy in the observing system is needed, especially to assist automatic quality control procedures. For instance, having XBT data in the vicinity of profiling floats can help detect errors in one or the other instrument.

AUTHOR CONTRIBUTIONS

GG led the writing and organization of the manuscript, as well as the research whose results are posted in several sections. JS led the research posted in several sections and contributed with writing and comments. FB, LC, MC, SD, RD, MG, HL, RM, UR, TR, RT, JT, NZ, MB, TB, RC, CD, KH, MK, MM, FR, CS, UB, and DV contributed to the writing of sections, posted comments, and provided figures.

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REFERENCES

Abraham, J. P., Baringer, M., Bindoff, N. L., Boyer, T., Cheng, L. J., Church, J. A., et al. (2013). A review of global ocean temperature observations: implications for ocean heat content estimates and climate change. *Rev. Geophys.* 51, 450–483. doi: 10.1002/rog.20022

Abraham, J. P., Gorman, J., Reseghetti, F., Sparrow, E., Stark, J., and Shepard,. T. (2014). Modeling and numerical simulation of the forces acting on a sphere during early-water entry. *Ocean Eng.* 76, 1–9. doi: 10.1016/j.oceaneng.2013.11.015

Abraham, J. P., Gorman, J. M., Reseghetti, F., Sparrow, E. M., and Minkowycz, W. J. (2012). Drag coefficients for rotating expendable bathythermographs and the impact of launch parameters on depth predictions. *Num. Heat Transfer Pt.* 62, 25–43. doi: 10.1080/10407782.2012.672898

Auad, G., Roemmich, D., and Gilson, J. (2011). The california current system in relation to the northeast pacific ocean circulation. *Prog. Oceanogr.* 91, 576–592. doi: 10.1016/j.pocean.2011.09.004

Bailey, R., Gronell, A. M., Phillips, H., Tanner, E., and Meyers, G. (1994). *Quality Control Cookbook for XBT Data*. CSIRO Marine Laboratories Reports 221.

Boyer, T., Domingues, C. M., Good, S. A., Johnson, G. C., Lyman, J. M., Ishii, M., et al. (2016). Sensitivity of global ocean heat content estimates to mapping methods, XBT bias corrections, and baseline climatologies. *J. Clim.* 29, 4817–4842. doi: 10.1175/JCLI-D-15-0801.1

Boyer, T. P., Antonov, J. I., Baranova, O. K., Coleman, C., Garcia, H. E., Grodsky (2013). *World Ocean Database 2013*. NOAA Atlas NESDIS 72.

Brannigan, L., Lenn, Y.-D., Rippeth, T. P., McDonagh, E., Chereskin, T. K., and Sprintall, J. (2013). Shear at the base of the oceanic mixed layer generated by wind shear alignment. *J. Phys. Oceanogr.* 43, 1798–1810. doi: 10.1175/JPO-D-12-0104.1

Bringas, F., and Goni, G. (2015). Early dynamics of deep blue XBT probes. *J. Atmos. Oceanic Tech.* 32, 2253–2263. doi: 10.1175/JTECH-D-15-0048.1

Cai, W., Shi, G., Cowan, T., Bi, D., and Ribbe, J. (2005). The response of the Southern Annular Mode, the East Australian Current, and the southern mid-latitude ocean circulation to global warming. *Geophys. Res. Lett.* 32:L23706. doi: 10.1029/2005GL024701

Chang, E. K. M., Lee, S., and Swanson, K. L. (2002). Storm track dynamics. *J. Clim.* 15, 2163–2183. doi: 10.1175/1520-0442(2002)015<02163:STD>2.0.CO;2

Cheng, L., Abraham, J., Goni, G., Boyer, T., Wijffels, S., Cowley, R., et al. (2016b). XBT science: assessment of instrumental biases and errors. *Bull. Amer. Met. Soc.* 97, 924–933. doi: 10.1175/BAMS-D-15-00031.1

Cheng, L., Luo, H., Boyer, T., Cowley, R., Abraham, J., Gouretski, V., et al. (2018). How well can we correct systematic errors in historical XBT data? *J. Atmos. Oceanic Tech.* 35, 1103–1125. doi: 10.1175/JTECH-D-17-0122.1

Cheng, L., Trenberth, K. E., Fasullo, J., Boyer, T., Abraham, J., and Zhu, J. (2017). Improved estimates of ocean heat content from 1960-2015. *Sci. Adv.* 3:e1601545. doi: 10.1126/sciadv.1601545

Cheng, L., Trenberth, K. E., Palmer, M. D., Zhu, J., and Abraham, J. P. (2016a). Observed and simulated full-depth ocean heat-content changes for 1970–2005. *Ocean Sci.* 12, 925–935. doi: 10.5194/os-12-925-2016

Cheng, L., and Zhu, J. (2016). Benefits of CMIP5 multimodel ensemble in reconstructing historical ocean subsurface temperature variations. *J. Clim.* 29, 5393–5416. doi: 10.1175/JCLI-D-15-0730.1

Cheng, L., Zhu, J., Cowley, R., Boyer, T., and Wijffels, S. (2014). Time, probe type and temperature variable bias corrections to historical expendable bathythermograph observations. *J. Atmos. Oceanic Tech.* 31, 1793–1825. doi: 10.1175/JTECH-D-13-00197.1

Ciuffardi, T., Napolitano, E., Iacono, R., Reseghetti, F., Raiteri, G., and Bordone, A. (2016). Analysis of surface circulation structures along a frequently repeated XBT transect crossing the Ligurian and Tyrrhenian Seas. *Ocean Dyn.* 66, 767–783. doi: 10.1007/s10236-016-0954-y

Cowley, R., Wijffels, S., Cheng, L., Boyer, T., and Kizu, S. (2013). Biases in expendable bathythermograph data: a new view based on historical side-by-side comparisons. *J. Atmos. Oceanic Tech.* 30, 1195–1225. doi: 10.1175/JTECH-D-12-00127.1

DiNezio, P. N., and Goni, G. (2010). Identifying and estimating biases between XBT and Argo observations using satellite altimetry. *J. Atmos. Oceanic Tech.* 27, 226–240. doi: 10.1175/2009JTECHO711.1

DiNezio, P. N., and Goni, G. (2011). Direct evidence of a changing fall-rate bias in XBT manufactured during 1986-2008. *J. Atmos. Oceanic Tech.* 28, 1569–1578. doi: 10.1175/JTECH-D-11-00017.1

Domingues, C. M., Church, J. A., White, N. J., Gleckler, P. J., Wijffels, S. E., Barker, P. M., et al. (2008). Improved estimates of upper-ocean warming and multi-decadal sea-level rise. *Nature* 453, 1090–1093. doi: 10.1038/nature07080

Domingues, R., Baringer, M., and Goni, G. (2016). Remote sources for year-to-year changes in the seasonality of the Florida current transport. *J.Geophys. Res.* 121, 7547–7559. doi: 10.1002/2016JC012070

Domingues, R., Goni, G., Baringer, M., and Volkov, D. (2018). What caused the accelerated sea level changes along the U.S. East Coast during 2010-2015? *Geophys. Res. Lett.* 45, 13,367–13,376. doi: 10.1029/2018GL081183

Domingues, R., Goni, G., Swart, S., and Dong, S. (2014). Wind forced variability of the antarctic circumpolar current south of Africa between 1993 and 2010. *J. Geophys. Res.* 119, 1123–1145. doi: 10.1002/2013JC008908

Domingues, R., Kuwano-Yoshida, A., Chardon-Maldonado, P., Todd, R. E., Halliwell, G. R., Kim, H. S., et al. (2019). Ocean observing systems in support of studies and forecasts of tropical and extratropical cyclones. *Front. Marine Sci.* 6:446. doi: 10.3389/fmars.2019.00446

Dong, S., Baringer, M., Goni, G., and Garzoli, S. (2011). Importance of the assimilation of Argo float measurements on the meridional overturning circulation in the South Atlantic. *Geophys. Res. Lett.* 38:L18603. doi: 10.1029/2011GL048982

Dong, S., Baringer, M. O., Goni, G. J., Meinen, C. S., and Garzoli, S. L. (2014). Seasonal variations in the South Atlantic meridional overturning circulation from observations and numerical models. *Geophys. Res. Lett.* 41, 4611–4618. doi: 10.1002/2014GL060428

Dong, S., Garzoli, S. L., Baringer, M. O., Meinen, C. S., and Goni, G. J. (2009). The atlantic meridional overturning circulation and its northward heat transport in the South Atlantic. *Geophys. Res. Lett.* 36:L20606. doi: 10.1029/2009GL039356

Dong, S., Gille, S. T., and Sprintall, J. (2007a). An assessment of the Southern ocean mixed layer heat budget. *J. Clim.* 20, 4425–4442. doi: 10.1175/JCLI4259.1

Dong, S., Gille, S. T., Sprintall, J., and Fetzer, E. J. (2010). Assessing the potential of the Atmospheric Infrared Sounder (AIRS) surface temperature and specific humidity in turbulent heat flux estimates in the southern ocean. *J. Geophys. Res.* 115:C05013. doi: 10.1029/2009JC005542

Dong, S., Gille, S. T., Sprintall, J., and Gentemann, C. (2006a). Validation of the advanced microwave scanning radiometer for the earth observing System (AMSR-E) sea surface temperature in the Southern Ocean. *J. Geophys. Res.* 111:C04002. doi: 10.1029/2005JC002934

Dong, S., Goni, G., and Bringas, F. (2015). Temporal variability of the South Atlantic meridional overturning circulation between 20°S and 35°S. *Geophys. Res. Lett.* 42, 7655–7662. doi: 10.1002/2015GL065603

Dong, S., Hautala, S. L., and Kelly, K. A. (2007b) Interannual variations in upper-ocean heat content and heat transport convergence in the western North Atlantic. *J. Phys. Oceanogr.* 37, 2682–2697. doi: 10.1175/2007JPO3645.1

Dong, S., Sprintall, J., and Gille, S. T. (2006b). Location of the Antarctic polar front from AMSR-E satellite sea surface temperature measurements. *J. Phys. Oceanogr.* 36, 2075–2089. doi: 10.1175/JPO2973.1

Douglass, E., Roemmich, D., and Stammer, D. (2009). Data sensitivity of the ECCO state estimate in a regional setting. *J. Atmos. Oceanic Tech.* 26, 2420–2443. doi: 10.1175/2009jtecho641.1

Douglass, E., Roemmich, D., and Stammer, D. (2010). Interannual variability in North Pacific heat and freshwater budgets. *Deep Sea Res.* 57, 1127–1140. doi: 10.1016/j.dsr2.2010.01.001

Durack, P. J., Glecker, P. J., Landerer, F. W., and Taylor, K. E. (2014). Quantifying underestimates of long-term upper-ocean warming. *Nat. Clim. Change* 4, 999–1005. doi: 10.1038/nclimate2389

Eigenheer, A., and Quadfasel, D. (2000). Seasonal variability of the Bay of Bengal circulation inferred from TOPEX/Poseidon altimetry. *J. Geophys. Res.* 105, 3243–3252. doi: 10.1029/1999JC900291

England, M. H., McGregor, S., Spence, P., Meehl, G. A., Timmermann, A., Cai, W., et al. (2014). Recent intensification of wind-driven circulation in the Pacific and the ongoing warming hiatus. *Nat. Clim. Change* 4, 222–227. doi: 10.1038/nclimate2106

Ezer, T. (2013). Sea level rise, spatially uneven and temporally unsteady: why the US East Coast, the global tide gauge record, and the global altimeter data show different trends. *Geophys. Res. Lett.* 40, 5439–5444. doi: 10.1002/2013GL057952

Fernandez, D., Bowen, M., and Sutton, P. (2018). Variability, coherence and forcing mechanisms in the New Zealand ocean boundary currents. *Prog. Oceanogr.* 165, 168–188. doi: 10.1016/j.pocean.2018.06.002

Firing, Y. L., Chereskin, T. K., and Mazloff, M. R. (2011). Vertical structure and transport of the antarctic circumpolar current in drake passage from direct velocity observations. *J. Geophys. Res.* 116:C08015. doi: 10.1029/2011JC006999

Fonseca, C., Goni, G. J., Johns, W. E., and Campos, E. J. D. (2004). Investigation of the North Brazil current retroflection and north equatorial countercurrent variability. *Geophys. Res. Lett.* 31:L21304. doi: 10.1029/2004GL020054

Frajka-Williams, E., Dong, S., Meinen, C., Perez, R., Goni, G., Volkov, D., et al. (2019). Atlantic Meridional overturning circulation: observed transports and mechanisms. *Front. Mar. Sci.* 6:260. doi: 10.3389/fmars.2019.00260

Fratantoni, D. M., O'Brien, J. K., Flagg, C., and Rossby, T. (2017). AXIS–An autonomous expendable instrument system. *J. Atmos. Oceanic Tech.* 34, 2673–2682. doi: 10.1175/JTECH-D-17-0054.1

Gleckler, P. J., Durack, P. J., Stouffer, R. J., Johnson, G. C., and Forest, C. E. (2016). Industrial-era global ocean heat uptake doubles in recent decades. *Nat. Clim. Change* 6, 394–398. doi: 10.1038/nclimate2915

Goes, M., Babcock, E., Bringas, F., Ortner, P., and Goni, G. (2017). The impact of improved thermistor calibration on the expendable bathythermograph profile data. *J. Atmos. Oceanic Tech.* 34, 1947–1961. doi: 10.1175/JTECH-D-17-0024.1

Goes, M., Baringer, M., and Goni, G. (2015b). The impact of historical biases on the XBT-derived meridional overturning circulation estimates at 34°S. *Geophys. Res. Lett.* 42, 1848–1855. doi: 10.1002/2014GL061802

Goes, M., Christophersen, J., Dong, S., Goni, G., and Baringer, M. O. (2018). An updated estimate of salinity for the atlantic ocean sector using temperature–salinity relationships. *J. Atmos. Oceanic Tech.* 35, 1771–1784. doi: 10.1175/JTECH-D-18-0029.1

Goes, M., Cirano, M., Mata, M. M., and Majumder, S. (2019). Long-term monitoring of the Brazil Current transport at 22S from XBT and altimetry data: Seasonal, interannual and extreme variability. *J. Geophys. Res.* 124, 3645–3663. doi: 10.1029/2018JC014809

Goes, M., Goni, G., and Dong, S. (2015a). An optimal XBT-based monitoring system for the South Atlantic meridional overturning circulation at 34°S. *J. Geophys. Res.* 120, 161–181. doi: 10.1002/2014JC010202

Goes, M., Goni, G., Hormann, V., and Perez, R. C. (2013a). Variability of the Atlantic off-equatorial eastward currents during 1993–2010 using a synthetic method. *J. Geophys. Res.* 118, 3026–3045. doi: 10.1002/jgrc.20186

Goes, M., Goni, G., and Keller, K. (2013b). Reducing biases in XBT measurements by including discrete information from pressure switches. *J. Atmos. Oceanic Tech.* 30, 810–824. doi: 10.1175/JTECH-D-12-00126.1

Goni, G., and Baringer, M. (2002). Surface currents in the tropical Atlantic across high density XBT line AX08. *Geophys. Res. Lett.* 29, 71.1–71.4. doi: 10.1029/2002GL015873

Goni, G., Roemmich, D., Molinari, R., Meyers, G., Sun, C., Boyer, T., et al. (2010). "The ship of opportunity program," in *Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society*, eds J. Hall, D. E. Harrison, and D. Stammer (Auckland: ESA Publications).

Goni, G. J., and Wainer, I. (2001). Investigation of the Brazil Current front variability from altimeter data. *J. Geophys. Res.* 106, 31,117–31,128. doi: 10.1029/2000JC000396

Good, S. A. (2011). Depth biases in XBT data diagnosed using bathymetry data. *J. Atmos. Oceanic Tech.* 28, 287–300. doi: 10.1175/2010JTECHO773.1

Gorman, J. M., Abraham, J. P., Schwalbach, D. B., Shepard, T. S., Stark, J. R., and Reseghetti, F. (2014). Experimental verification of drag forces on spherical objects entering water. *J. Mar. Ocean Biol. Oceanogr.* 3:2. doi: 10.4172/2324-8661.1000126

Gould, J., Roemmich, D., Wijffels, S., Freeland, H., Ignaszewsky, M., Jianping, X., et al. (2004). Argo profiling floats bring new era of in situ ocean observations. *Eos Trans. Amer. Geophys.* 179, 190–191. doi: 10.1029/2004EO190002

Gouretski, V. (2012). Using GEBCO digital bathymetry to infer depth biases in the XBT data. *Deep Sea Res.* 62, 40–52. doi: 10.1016/j.dsr.2011.12.012

Gouretski, V., and Reseghetti, F. (2010). On depth and temperature biases in bathythermograph data: Development of a new correction scheme based on analysis of a global ocean database. *Deep Sea Res.* 57, 812–833. doi: 10.1016/j.dsr.2010.03.011

Green, A. W. (1984). Bulk dynamics of the expendable bathythermograph (XBT). *Deep-Sea Res.* 31, 415–426. doi: 10.1016/0198-0149(84)90093-1

Hamon, M., Reverdin, G., and Le Traon, P. Y. (2012). Empirical correction of XBT data. *J. Atmos. Oceanic Tech.* 29, 960–973. doi: 10.1175/JTECH-D-11-00129.1

Hanawa, K., Rual, P., Bailey, R., Sy, A., and Szabados, M. (1995). A new depth time equation for Sippican or TSK T-7, T-6 and T-4 expendable bathythermographs (XBT). *Deep Sea Res.* 42, 1423–1451. doi: 10.1016/0967-0637(95)97154-Z

Hill, K. L., Rintoul, S. R., Coleman, R., and Ridgway, K. R. (2008). Wind forced low frequency variability of the East Australian current. *Geophys. Res. Lett.* 35:L08602. doi: 10.1029/2007GL032912

Hill, K. L., Rintoul, S. R., Ridgway, K. R., and Oke, P. R. (2011). Decadal changes in the South Pacific western boundary current system revealed in observations and ocean state estimates. *J. Geophys. Res.* 116:C01009. doi: 10.1029/2009JC005926

Holbrook, N. J., and Maharaj, A. M. (2008). Southwest Pacific subtropical mode water: a climatology. *Prog. Oceanogr.* 77, 298–315. doi: 10.1016/j.pocean.2007.01.015

Hoskins, B. J., and Hodges, K. I. (2002). New perspectives on the Northern Hemisphere winter storm tracks. *J. Atmos. Sci.* 59, 1041–1061. doi: 10.1175/1520-0469(2002)059<1041:NPOTNH>2.0.CO;2

Houpert, L., Testor, P., Durrieu de Madron, X., Somot, S., D'Ortenzio, F., Estournel, C., et al. (2015). Seasonal cycle of the mixed layer, the seasonal thermocline and the upper-ocean heat storage rate in the Mediterranean Sea derived from observations. *Prog. Oceanogr.* 132, 333–352. doi: 10.1016/j.pocean.2014.11.004

Ishii, M., Fukuda, Y., Hirahara, S., Yasui, S., Suzuki, T., and Sato, K. (2017). Accuracy of global upper ocean heat content estimation expected from present observational data sets. *SOLA* 13, 163–167. doi: 10.2151/sola.2017-030

Jayne, S. R., Roemmich, D., Zilberman, N., Riser, S. C., Johnson, K. S., Johnson, G. C., et al. (2017). The argo program: present and future. *Oceanography* 30, 18–28. doi: 10.5670/oceanog.2017.213

Jiang, C., Gille, S. T., Sprintall, J., and Sweeney, C. (2014). Drake Passage oceanic pCO2: evaluating CMIP5 coupled carbon–climate models using *in-situ* observations. *J. Clim.* 27, 76–100, doi: 10.1175/JCLI-D-12-00571.1

Joyce, T. M., Kwon, Y.-O., and Yu, L. (2009). On the relationship between synoptic wintertime atmospheric variability and path shifts in the Gulf Stream and Kuroshio extension. *J. Clim.* 22, 3177–3192. doi: 10.1175/2008JCLI2690.1

Kelly, K. A., Small, R. J., Samelson, R. M., Qiu, B., Joyce, T. M., Kwon, Y.-O., et al. (2010). Western boundary currents and frontal air–sea interaction: Gulf Stream and Kuroshio Extension. *J. Clim.* 23, 5644–5667. doi: 10.1175/2010JCLI3346.1

Kushnir, Y., Robinson, W. A., Blade, I., Hall, N. M. J., Peng, S., and Sutton, R. (2002). Atmospheric GCM response to extratropical SST anomalies: synthesis and evaluation. *J. Clim.* 15, 2233–2256. doi: 10.1175/1520-0442(2002)015<2233:AGRTES>2.0.CO;2

Kwon, Y.-O., Alexander, M. A., Bond, N. A., Frankignoul, C., Nakamura, H., Qiu, B., et al. (2010). Role of the Gulf Stream and Kuroshio–Oyashio systems in large-scale atmosphere–ocean interaction: a review. *J. Clim.* 23, 3249–3281. doi: 10.1175/2010JCLI3343.1

Latif, M., Arpe, K., and Roeckner, E. (2000). Oceanic control of decadal North atlantic sea level pressure variability in winter. *Geophys. Res. Lett.* 27, 727–730. doi: 10.1029/1999GL002370

Lee, S.-K., Park, W., Baringer, M. O., Gordon, A. L., Huber, B., and Liu, Y. (2015). Pacific origin of the abrupt increase in Indian Ocean heat content during the warming hiatus. *Nat. Geosci.* 8, 445–449. doi: 10.1038/ngeo2438

Legler, D. M., Freeland, H. J., Lumpkin, R., Ball, G., McPhaden, M. J., North, S., et al. (2015). The current status of the real-time *in situ* global ocean observing system for operational oceanography. *J. Oper. Oceanogr.* 8, s189–s200. doi: 10.1080/1755876X.2015.1049883

Lenn, Y.-D., and Chereskin, T. K. (2009). Observations of Ekman currents in the Southern Ocean. *J. Phys. Oceanogr.* 39, 768–779. doi: 10.1175/2008JPO3943.1

Lenn, Y.-D., Chereskin, T. K., and Sprintall, J. (2008). Improving estimates of the antarctic circumpolar current streamlines in drake passage. *J. Phys. Oceanogr.* 38, 1000–1010, doi: 10.1175/2007JPO3834.1

Lenn, Y.-D., Chereskin, T. K., Sprintall, J., and Firing, E. (2007). Mean jets, mesoscale variability and eddy momentum fluxes in the surface layer of the antarctic circumpolar current in drake passage. *J. Mar. Res.* 65, 27–58. doi: 10.1357/002224007780388694

Lenn, Y.-D., Chereskin, T. K., Sprintall, J., and McClean, J. L. (2011). Near-surface eddy heat and momentum fluxes in the antarctic circumpolar current in drake passage. *J. Phys. Oceanogr.* 41, 1385–1407. doi: 10.1175/JPO-D-10-05017.1

Levitus, S., Antonov, J. I., Boyer, T. P., Baranova, O. K., Garcia, H. E., Locarnini, R. A., et al. (2012). World ocean heat content and thermosteric sea level change (0-2000 m), 1955-2010. *Geophys. Res. Lett.* 39:L10603. doi: 10.1029/2012GL051106

Levitus, S., Antonov, J. I., Boyer, T. P., Locarnini, R. A., Garcia, H. E., and Mishonov, A. V. (2009). Global ocean heat content 1955-2008 in light of recently revealed instrumentation problems. *Geophys. Res. Lett.* 36:L07608. doi: 10.1029/2008GL037155

Li, Y., Han, W., Hu, A., Meehl, G. A., and Wang, F. (2018). Multidecadal changes of the upper Indian Ocean heat content during 1965–2016. *J. Clim.* 31, 7863–7884. doi: 10.1175/JCLI-D-18-0116.1

Lima, M. O., Cirano, M., Mata, M., Goes, M., Goni, G., and Baringer, M. O. (2016). An assessment of the Brazil Current baroclinic structure and variability near 22°S in distinct ocean forecasting and analysis systems. *Ocean Dyn.* 66, 893–916. doi: 10.1007/s10236-016-0959-6

Liu, Q.-Y., Feng, M., Wang, D., and Wijffels, S. (2015). Interannual variability of the Indonesian throughflow transport: a revisit based on 30 year expendable bathythermograph data. *J. Geophys. Res.* 120, 8270–8282. doi: 10.1002/2015JC011351

Lopez, H., Dong, S., Lee, S.-K., and Goni, G. (2016). Decadal modulations of interhemispheric global atmospheric circulations and monsoons by the South Atlantic meridional overturning circulation. *J. Clim.* 29, 1831–1851. doi: 10.1175/JCLI-D-15-0491.1

Lopez, H., Goni, G., and Dong, S. (2017). A reconstructed South Atlantic meridional overturning circulation time series since 1870. *Geophys. Res. Lett.* 44, 3309–3318. doi: 10.1002/2017GL073227

Lyman, J. M., Good, S. A., Gouretski, V. V., Ishii, M., Johnson, G. C., Palmer, M. D., et al. (2010). Robust warming of the global upper ocean. *Nature* 465, 334–337. doi: 10.1038/nature09043

Lyman, J. M., and Johnson, G. C. (2008). Estimating annual global upper-ocean heat content anomalies despite irregular *in situ* ocean sampling. *J. Clim.* 21, 5629–5641. doi: 10.1175/2008JCLI2259.1

Majumder, S., Goes, M., Polito, P. S., Lumpkin, R., Schmid, C., and Lopez, H. (2019). Propagating modes of variability and their impact on the western boundary current in the South Atlantic. *J. Geophys. Res.* 124, 3168–3185. doi: 10.1029/2018JC014812

Martin, M. J., Balmaseda, M., Bertino, L., Brasseur, P., Brassington, G., Cummings, et al. (2015). Status and future of data assimilation in operational oceanography. *J. Oper. Oceanogr.* 8, s28–s48. doi: 10.1080/1755876X.2015.1022055

McCaskill, C., Shay, L. K., Brewster, J. K., and Meyers, P. C. (2016). Development and assessment of the systematically merged Pacific Ocean regional temperature and salinity (SPORTS) climatology for ocean heat content estimations. *J. Atmos. Oceanic Tech.* 33, 2259–2272. doi: 10.1175/JTECH-D-15-0168.1

Mill, G. N., da Costa, V. S., Lima, N. D., Gabioux, M., Guerra, L. A. A., and Paiva, A. M. (2015). Northward migration of Cape São Tomé rings, Brazil. *Cont. Shelf Res.* 106, 27–37. doi: 10.1016/j.csr.2015.06.010

Molinari, R. L. (2004). Annual and decadal variability in the western subtropical North Atlantic: signal characteristics and sampling methodologies. *Prog. Oceanogr.* 62, 33–66. doi: 10.1016/j.pocean.2004.07.002

Molinari, R. L. (2011). Information from low-density expendable bathythermograph transects: North Atlantic mean temperature structure and quasi-decadal variability. *Prog. Oceanogr.* 88, 131–149. doi: 10.1016/j.pocean.2010.12.013

Morrow, R., Donguy, J.-R., Chaigneau, A., and Rintoul, S. R. (2004). Cold core anomalies at the subantarctic front, south of Tasmania. *Deep Sea Res.* 51, 1417–1440. doi: 10.1016/j.dsr.2004.07.005

Morrow, R., and Kestenare, E. (2014). Nineteen-year changes in surface salinity in the Southern Ocean south of Australia. *J. Mar. Sys.* 129, 472–483. doi: 10.1016/j.jmarsys.2013.09.011

Morrow, R., Valladeau, G., and Sallée, J. (2008). Observed subsurface signature of Southern Ocean decadal sea level rise. *Prog. Oceanogr.* 77, 351–366. doi: 10.1016/j.pocean.2007.03.002

Munro, D. R., Lovenduski, N. S., Stephens, B. B., Newberger, T., Arrigo, K. R., Takahashi, T., et al. (2015). Estimates of net community production in the Southern Ocean determined from time series observations (2002–2011) of nutrients, dissolved inorganic carbon, and surface ocean pCO2 in drake passage. *Deep Sea Res.* 114, 49–63. doi: 10.1016/j.dsr2.2014.12.014

Nagano, A., Ichikawa, H., Yoshikawa, Y., Kizu, S., and Hanawa, K. (2012). Variation of the southward interior flow of the North Pacific subtropical gyre, as revealed by a repeat hydrographic survey. *J. Oceanogr.* 68, 361–368. doi: 10.1007/s10872-012-0102-3

Nagano, A., Kizu, S., Hanawa, K., and Roemmich, D. (2016). Heat transport variation due to change of North Pacific subtropical gyre interior flow during 1993–2012. *Ocean Dyn.* 66, 1637–1649. doi: 10.1007/s10236-016-1007-2

Nakamura, H., Sampe, T., Tanimoto, Y., and Shimpo, A. (2004). "Observed associations among storm tracks, jet streams and midlatitude oceanic fronts," in *Earth's Climate: The Ocean–Atmosphere Interaction, Geophysical Monograph*, Vol. 147, *American Geophysical Union* (Washington, DC), 329–346. doi: 10.1029/147GM18

Napolitano, E., Iacono, R., Ciuffardi, T., Reseghetti, F., Poulain, P. M., and Notarstefano, G. (2018). The Tyrrhenian Intermediate Water (TIW): characterization and formation mechanisms. *Prog. Oceanogr.* 170, 53–68. doi: 10.1016/j.pocean.2018.10.017

Nieves, V., Willis, J. K., and Patzert, W. C. (2015). Recent hiatus caused by decadal shift in Indo-Pacific heating. *Science* 349, 532–535. doi: 10.1126/science.aaa4521

Oke, P. R., Larnicol, G., Fujii, V., Smith, G. C., Lea, D. J., Guinehut, S., et al. (2015a). Assessing the impact of observations on ocean forecasts and reanalyses: Part 1, Global studies. *J. Oper. Oceanogr.* 8, s49–s62. doi: 10.1080/1755876X.2015.1022067

Oke, P. R., Larnicol, G., Jones, E. M., Kourafalou, V., Sperrevik, A. K., Carse, F., et al. (2015b). Assessing the impact of observations on ocean forecasts and reanalyses: Part 2, Regional applications. *J. Oper. Oceanogr.* 8, s63–s79. doi: 10.1080/1755876X.2015.1022080

Olson, D. B., Brown, O. B., and Emmerson, S. R. (1983). Gulf Stream frontal statistics from Florida Straits to Cape Hatteras derived from satellite and historical data. *J. Geophys. Res.* 88, 4569–4577. doi: 10.1029/JC088iC08p04569

Pezzi, L. P., Souza, R. B., Farias, P. C., Acevedo, O., and Miller, A. J. (2016). Air-sea interaction at the Southern Brazilian Continental shelf: *in situ* observations. *J. Geophys. Res.* 121, 6671–6695. doi: 10.1002/2016JC011774

Pilo, G. S., Oke, P. R., Rykova, T., Coleman, R., and Ridgway, K. (2015). Do East Australian current anticyclonic eddies leave the Tasman Sea? *J. Geophys. Res.* 120, 8099–8114. doi: 10.1002/2015JC011026

Polton, J. A., Lenn, Y. D., Elipot, S., Chereskin, T. K., and Sprintall, J. (2013). Can drake passage observations match Ekman's classic theory? *J. Phys. Oceanogr.* 43, 1733–1740. doi: 10.1175/JPO-D-13-034.1

Reseghetti, F., Cheng, L., Borghini, M., Yashayaev, I. M., Raiteri, G., and Zhu, J. (2018). Assessment of quality and reliability of measurements with XBT Sippican T5 and T5/20. *J. Atmos. Oceanic Tech.* 35, 1935–1960. doi: 10.1175/JTECH-D-18-0043.1

Rhein, M., Rintoul, S. R., Aoki, S., Campos, E., Chambers, D., Feely, R. A., et al. (2013). "Observations: ocean," in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (Cambridge, UK; New York, NY: Cambridge University Press), 255–315.

Ribotti, A., Sorgente, R., Olita, A., Orilia, F., Borghini, M., and Reseghetti, F. (2016). Indication of recent warming process at the intermediate level in the Tyrrhenian Sea from SOOP XBT measurements. *Mediter. Mar. Sci.* 17, 467–475. doi: 10.12681/mms.1196

Ridgway, K. R., Coleman, R. C., Bailey, R. J., and Sutton, P. (2008). Decadal variability of East Australian current transport inferred from repeated high-density XBT transects, a CTD survey and satellite altimetry. *J. Geophys. Res.* 113:C08039. doi: 10.1029/2007JC004664

Ridgway, K. R., and Dunn, J. R. (2003). Mesoscale structure of the mean East Australian Current System and its relationship with topography. *Prog. Oceanogr.* 56, 189–222. doi: 10.1016/S0079-6611(03)00004-1

Rintoul, S. R., Sokolov, S., and Church, J. (2002). A 6 year record of baroclinic transport variability of the Antarctic circumpolar current at 140°E from expendable bathythermograph and altimetry measurements. *J. Geophys. Res.* 107:19-1-19-22. doi: 10.1029/2001JC000787

Riser, S. C., Freeland, H. J., Roemmich, D., Wijffels, S., Troisi, A., Belbéoch, M., et al. (2016). Fifteen years of ocean observations with the global Argo array. *Nat. Clim. Change* 6, 145–153. doi: 10.1038/nclimate2872

Roemmich, D., and Cornuelle, B. (1992). The subtropical mode waters of the South Pacific Ocean. *J. Phys. Oceanogr.* 22, 1178–1187. doi: 10.1175/1520-0485(1992)022<1178:TSMWOT>2.0.CO;2

Roemmich, D., and Gilson, J. (2001). Eddy transport of heat and thermocline waters in the North Pacific: a key to interannual/decadal climate variability? *J. Phys. Oceanogr.* 31, 675–688. doi: 10.1175/1520-0485(2001)031<0675:ETOHAT>2.0.CO;2

Roemmich, D., Gilson, J., Davis, R., Sutton, P., Wijffels, S., and Riser, S. (2007). Decadal spin up of the deep subtropical gyre in the South Pacific. *J. Phys. Oceanogr.* 37, 162–173. doi: 10.1175/JPO3004.1

Roemmich, D., Gilson, J., Willis, J., Sutton, P., and Ridgway, K. (2005). Closing the time-varying mass and heat budgets for large ocean areas: the Tasman box. *J. Clim.* 18, 2330–2343. doi: 10.1175/JCLI3409.1

Rossby, T., Flagg, C., Chafik, L., Harden, B., and Søiland, H. (2018). A direct estimate of volume, heat, and freshwater exchange across the Greenland-Iceland-Faroe-Scotland Ridge. *J. Geophys. Res.* 123, 7139–7153. doi: 10.1029/2018JC014250

Rossby, T., Flagg, C., and Donohue, K. (2010). On the variability of Gulf Stream transport from seasonal to decadal timescales. *J. Mar. Res.* 68, 503–522. doi: 10.1357/002224010794657128

Rudnick, D. L. (2016). Ocean research enabled by underwater gliders. *Ann. Rev. Mar. Sci.* 8, 519–541. doi: 10.1146/annurev-marine-122414-033913

Sallée, J. B., Speer, K., and Morrow, R. (2008). Response of the Antarctic circumpolar current to atmospheric variability. *J. Clim.* 21, 3020–3039. doi: 10.1175/2007JCLI1702.1

Schroeder, K., Chiggiato, J., Josey, S. A., Borghini, M., Aracri, S., and Sparnocchia, S. (2017). Rapid response to climate change in a marginal sea. *Scien. Rep.* 7:4065. doi: 10.1038/s41598-017-04455-5

Shay, L. K., and Brewster, J. K. (2010). Oceanic heat content variability in the eastern Pacific Ocean for hurricane intensity forecasting. *Mon. Wea. Rev.* 138, 2110–2131. doi: 10.1175/2010MWR3189.1

Shepard, T., Abraham, J. P., Schwalbach, D. S., Kane, S., Sigling, D., and Harrington, T. (2014). Velocity and density effect on impact force during water entry of spheres. *J. Geophys. Remote Sens.* 3:129. doi: 10.4172/2169-0049.1000129

Sherin, V. R., Durand, F., Gopalkrishna, V. V., Anuvinda, S., Chaitanya, A. V. S., Bourdalle-Badie, R., et al. (2018). Signature of indian Ocean dipole on the western boundary current of the Bay of Bengal. *Deep Sea Res.* 136, 91–106. doi: 10.1016/j.dsr.2018.04.002

Shi, J.-R., Xie, S.-P., and Talley, L. D. (2018). Evolving relative importance of the Southern Ocean and North Atlantic in anthropogenic ocean heat uptake. *J. Clim.* 31, 7459–7479. doi: 10.1175/JCLI-D-18-0170.1

Sloyan, B. M., Ridgway, K. R., and Cowley, R. (2016). The east australian current and property transport at 27°S from 2012 to 2013. *J. Phys. Oceanogr.* 46, 993–1008. doi: 10.1175/JPO-D-15-0052.1

Smith, N., Harrison, D., Bailey, R., Alves, O., Delcroix, T., Roemmich, K., et al. (2001). "The upper ocean thermal network," in *From: Observing the Oceans in the 21st Century*, eds C. Koblinsky and N. Smith (Melbourne, VIC: Bureau of Meteorology), 259–284.

Sprintall, J. (2003). Subsurface structure of interannual temperature anomalies in the Australian sector of the Southern Ocean. *J. Geophys. Res.* 108:3285. doi: 10.1029/2002JC001494

Sprintall, J. (2008). Long-term trends and interannual variability of temperature in Drake Passage. *Prog. Oceanogr.* 77, 316–330. doi: 10.1016/j.pocean.2006.06.004

Sprintall, J., Chereskin, T. K., and Sweeney, C. (2012). High-resolution underway upper ocean and surface atmospheric observations in Drake Passage: synergistic measurements for climate science. *Oceanography* 25, 70–81. doi: 10.5670/oceanog.2012.77

Sprintall, J., Gordon, A. L., Wijffels, S. E., Feng, M., Hu, S., Koch-Larrouy, A., et al. (2019). Detecting change in the Indonesian seas. *Front. Mar. Sci.* 6:257. doi: 10.3389/fmars.2019.00257

Stephenson, G. R., Gille, S. T., and Sprintall, J. (2012). Seasonal variability of upper ocean heat content in Drake Passage. *J. Geophys. Res.* 117:C04019. doi: 10.1029/2011JC007772

Stephenson, G. R., Gille, S. T., and Sprintall, J. (2013). Processes controlling upper-ocean heat content in Drake Passage. *J. Geophys. Res.* 118, 4409–4423. doi: 10.1002/jgrc.20315

Suthers, I. M., Young, J. W., Baird, M. E., Roughan, M., Everett, J. E., Brassington, G. B., et al. (2011). The strengthening East Australian Current, its eddies and biological effects - an introduction and overview. *Deep Sea Res.* 58, 538–546. doi: 10.1016/j.dsr2.2010.09.029

Swart, N. C., Gille, S. T., Fyfe, J. C., and Gillett, N. P. (2018). Recent Southern Ocean warming and freshening driven by greenhouse gas emissions and ozone depletion. *Nat. Geosci.* 11, 836–841. doi: 10.1038/s41561-018-0226-1

Swart, S., Speich, S., Ansorge, I. J., Goni, G. J., Gladyshev, S., and Lutjeharms, J. R. E. (2008). Transport and variability of the Antarctic Circumpolar Current south of Africa. *J. Geophys. Res.* 113:C09014. doi: 10.1029/2007JC004223

Thadathil, P., Ghosh, A. K., Sarupria, J. S., and Gopalakrishna, V. V. (2001). An interactive graphical system for XBT data quality control and visualization. *Comp. Geosci.* 27, 867–876. doi: 10.1016/S0098-3004(00)00172-2

Thadathil, P., Saran, A. K., Gopalakrishna, V. V., Vethamony, P., and Araligidad, N. (2002). XBT fall rate in waters of extreme temperature: a case study in the Antarctic Ocean. *J. Atmos. Oceanic Tech.* 19, 391–397. doi: 10.1175/1520-0426-19.3.391

Thompson, A. F., Gille, S. T., MacKinnon, J. A., and Sprintall, J. (2007). Spatial and temporal patterns of small-scale mixing in Drake Passage. *J. Phys. Oceanogr.* 37, 572–592. doi: 10.1175/JPO3021.1

Todd, R., Goes, M., Baringer, M., Dong, S., Goni, G., Volkov, D., et al. (2019). Global Perspectives on observing ocean boundary current systems. *Front. Marine Sci.* 6:423. doi: 10.3389/fmars.2019.00423

Tonani, M., Balmaseda, M., Bertino, L., Blockley, E., Brassington, G., Davidson, F., et al. (2015). Status and future of global and regional ocean prediction systems. *J. Oper. Oceanogr.* 8, s201–s220. doi: 10.1080/1755876X.2015.1049892

Tsubouchi, T., Suga, T., and Hanawa, K. (2007). Three types of South Pacific subtropical mode waters: Their relation to the large-scale circulation of the South Pacific Subtropical Gyre and their temporal variability. *J. Phys. Oceanogr.* 37, 2478–2490. doi: 10.1175/JPO3132.1

Uehara, H., Kizu, S., Hanawa, K., Yoshikawa, Y., and Roemmich, D. (2008). Estimation of heat and freshwater transports in the North Pacific using high-resolution expendable bathythermograph data. *J. Geophys. Res.* 113:C02014. doi: 10.1029/2007JC004165

Verdy, A., Cornuelle, B., Mazloff, M. R., and Rudnick, D. L. (2017). Estimation of the tropical pacific ocean state 2010-13. *J. Atmos. Oceanic Tech.* 34, 1501–1517. doi: 10.1175/JTECH-D-16-0223.1

Vignudelli, S., Cipollini, P., Reseghetti, F., Fusco, G., Gasparini, G. P., and Manzella, G. M. R. (2003). Comparison between XBT data and TOPEX/Poseidon satellite altimetry in the ligurian-tyrrhenian area. *Ann. Geophys. Atmos. Hydrospheres Space Sci.* 21, 123–135. doi: 10.5194/angeo-21-123-2003

Von Schuckmann, K., Le Traon, P. Y., Aaboe, S., Fanjul, E. A., Autret, E., and Axell, L. (2018). Copernicus marine service ocean state report. *J. Oper. Oceanogr.* 11, S1–S142. doi: 10.1080/1755876X.2018.1489208

Wang, B., Liu, J., Kim, H.-J., Webster, P. J., and Yim, S.-Y. (2012). Recent change of the global monsoon precipitation (1979–2008). *Clim. Dyn.* 39, 1123–1135. doi: 10.1007/s00382-011-1266-z

Wijffels, S., and Meyers, G. (2004). An intersection of oceanic waveguides: variability in the indonesian throughflow region. *J. Phys. Oceanogr.* 34, 1232–1253. doi: 10.1175/1520-0485(2004)034<1232:AIOOWV>2.0.CO;2

Wijffels, S. E., Willis, J., Domingues, C. M., Barker, P., White, N. J., Gronell, A., et al. (2008). Changing expendable bathythermograph fall rates and their impact on estimates of thermosteric sea level rise. *J. Clim.* 21, 5657–5672. doi: 10.1175/2008JCLI2290.1

WMO (2015a). *Manual on Codes. Vol. I.2.* WMO-306. WMO, Geneva. ISBN:978-92-63-10306-2.

WMO (2015b). *Manual on the Global Telecommunication System.* WMO-386. WMO, Geneva. ISBN: 978-92-63-10386-4.

Zilberman, N. V., Roemmich, D. H., Gille, S. T., and Gilson, J. (2018). Estimating the velocity and transport of western boundary current systems: a case study of the East Australian Current near Brisbane. *J. Atmos. Oceanic Tech.* 35, 1313–1329. doi: 10.1175/JTECH-D-17-0153.1

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frontiers in Marine Science

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The Scientific and Societal Uses of Global Measurements of Subsurface Velocity

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Ocean velocity defines ocean circulation, yet the available observations of subsurface velocity are under-utilized by society. The first step to address these concerns is to improve visibility of and access to existing measurements, which include acoustic sampling from ships, subsurface float drifts, and measurements from autonomous vehicles. While multiple programs provide data publicly, the present difficulty in finding, understanding, and using these data hinder broader use by managers, the public, and other scientists. Creating links from centralized national archives to project specific websites is an easy but important way to improve data discoverability and access. A further step is to archive data in centralized databases, which increases usage by providing a common framework for disparate measurements. This requires consistent data standards and processing protocols for all types of velocity measurements. Central dissemination will also simplify the creation of derived products tailored to end user goals. Eventually, this common framework will aid managers and scientists in identifying regions that need more sampling and in identifying methods to fulfill those demands. Existing technologies are capable of improving spatial and temporal sampling, such as using ships of opportunity or from autonomous platforms like gliders, profiling floats, or Lagrangian floats. Future technological advances are needed to fill sampling gaps and increase data coverage.

Keywords: velocity, ocean measurements, subsurface, database, sampling network, ADCP, autonomous vehicle, floats

INTRODUCTION

Ocean circulation plays a critical role in the Earth's climate and biosphere through transport of heat, freshwater, momentum, nutrients, and biota. Ocean circulation, in turn, arises from ocean velocity that is driven by processes on a wide range of temporal and spatial scales. Although most of our knowledge of ocean circulation derives from indirect measurements (e.g., subsurface density or sea surface height), such measurements assume a low-frequency balance (geostrophy) that is incomplete. For this reason, direct measurements of subsurface ocean velocity are indispensable for a full diagnosis of ocean circulation. Better organization and dissemination of such measurements to societal users will increase the utility of historic, on-going, and future measurements.

Velocity measurements from the surface through the mixed layer to the abyss complement our indirect knowledge from density observations. For example, a pioneering use of public temperature and salinity data to calculate geostrophic velocity (Reid, 1994) traced deep boundary currents along the western continental slope of the North Atlantic. At the time, the currents were thought to be continuous along the slope. Seeding these currents with subsurface drifting floats (Bower et al., 2009), however, showed a striking lack of continuity and the prevalence of interior recirculation. Many other types of motion are responsible for the wide range of ocean variability observed: planetary waves (Gill, 1982), baroclinic instability and eddy generation in strong currents (Pedlosky, 1979), internal waves, transfer of wind momentum into the deep ocean (Sanford et al., 2007; Uhlhorn and Shay, 2012; Kilbourne and Girton, 2015), or ocean mixing (MacKinnon et al., 2017). Direct-velocity measurements provide greater insight into these processes than the indirect inferences from the ocean density field. Moreover, geostrophy does not apply at the equator, and is less significant at weakly stratified high latitudes where strong depth-averaged motion results from atmospheric forcing.

This article is spurred by a sense that the marine community has limited knowledge of existing ocean velocity sampling. Consider two anecdotes. An ocean engineer needs to identify the maximum force a subsurface structure can withstand and seeks maps of observed subsurface velocity. Not knowing of any local observations, the engineer's team turns instead to numerical models. Without personal contacts familiar with local direct velocity measurements, the ocean engineer assumes that existing information is adequate. In another example, to understand larval transport, a researcher requests maps of deep ocean velocity. With only maps of mean geostrophic circulation from historical hydrography, the important turbulent dispersion of biota is neglected. Although anecdotal, these two examples are a subset of our personal experiences and accurately reflect an inadequacy of the present situation.

Many marine fields are influenced by ocean currents and could benefit from existing observations. Example applications include larval dispersal for management of fisheries and ecosystems, oil spill response to deep or surface release (Hamilton et al., 2011, search and rescue operations, monitoring and tracking harmful algal blooms, coastal water quality monitoring, and marine engineering applications. With this article, we summarize present-day sampling capabilities and suggest improvements to data accessibility, as a first step to increase societal use of subsurface velocity measurements. Our suggestions to reach this goal deserve further discussion, modification, and implementation by scientists who measure ocean velocity, funders of this research, and potential users.

MEASURING SUBSURFACE OCEAN VELOCITY

Ocean velocity is measured by a variety of techniques with differing temporospatial response. An overview of common sensors or techniques is needed to understand how to create common frameworks from disparate measurements. Selected examples (**Figure 1**) convey the insight provided by velocity sampling.

Sensor Techniques

Acoustic Doppler

Acoustic Doppler current measurements rely on the frequency shift of an acoustic signal when it reflects off of a moving body. Acoustic Doppler current profilers (ADCPs) transmit acoustic pulses and fit Doppler shifts to gated time bins, thus providing a profile of along-beam velocity. Acoustic beams oriented in multiple directions resolve currents in 2 or 3 dimensions. Typically, ensembles of single-ping estimates are averaged over a few minutes to improve signal-to-noise ratios. Modern systems installed on ships can typically reach 900–1200 m at 38 kHz or 50–80 m at 300 kHz, and sometimes deeper under ideal conditions. Five-beam systems with a central beam pointing upwards are available to measure vertical velocity (e.g., Guerra and Thomson, 2017).

Acoustic Doppler current profilers can be installed on fixed moorings or on moving platforms. Any platform motion present needs to be removed during processing. Moving platforms include surface ships (shipboard ADCP, sADCP, see **Figure 1a**), CTD rosettes (lowered ADCP; Fischer and Visbeck, 1993), or increasingly on small autonomous platforms such as subsurface gliders (Todd et al., 2017) or surface autonomous vehicles (Thomson and Girton, 2017). The depth of ADCP sampling is only constrained by its platform.

Lagrangian Tracking

Acoustic tracking of subsurface floats provides estimates of averaged Lagrangian velocity between positions fixes (see Rossby and Özgökmen, 2007). Long range acoustic tracking is possible because of a sound guide at 700–1000 m throughout much of the global ocean. This fact permits successful tracking down to 4000 m with a few moored sound sources transmitting a few times per day. When applied to tracking 10–100 floats that follow a constant pressure or seawater density surface (RAFOS floats; Levine et al., 1986; Rossby et al., 1986; Richardson, 2018), this method traces advective-diffusive pathways of water parcels over years. For example, a recent study in the deep subpolar North Atlantic (**Figure 1b**; Bower et al., 2009) found that the Deep Western Boundary Current is remarkably leaky to the interior basin despite being topographically trapped. This tracking method is also useful in Polar Regions where ice hinders surface tracking (Chamberlain et al., 2018). Multicycle profiling floats can also estimate their subsurface drift velocity from surface GPS fixes (Lebedev et al., 2007), typically over a 10-day interval, while frequent surface fixes track surface drifters (Lumpkin et al., 2016a).

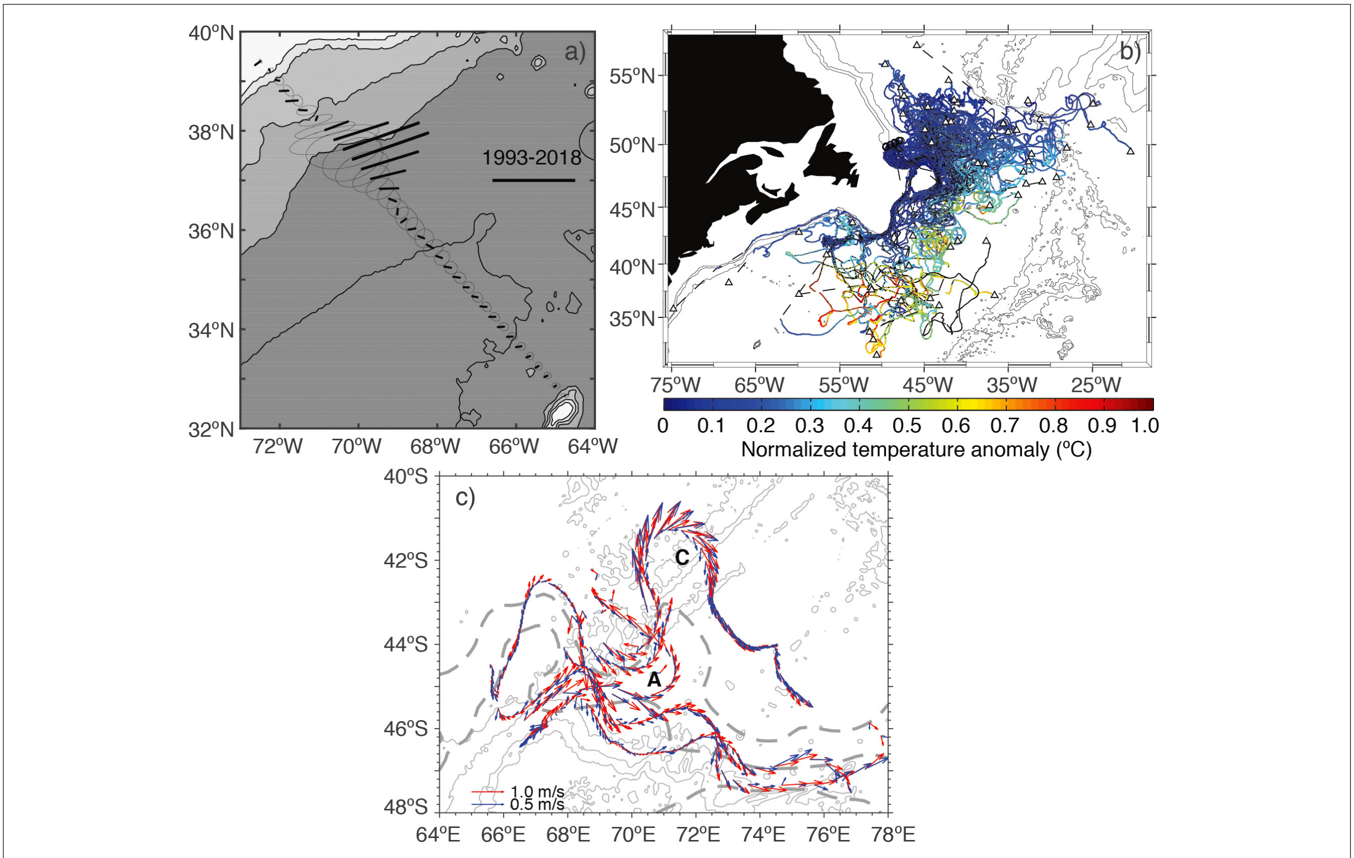

FIGURE 1 | Examples of velocity data. **(a)** Variance ellipses from repeated Shipboard ADCP transects across the Gulf Stream (e.g. Rossby et al., 2010). Long time-series are needed to show that variability on the flanks is directed toward the center of the Gulf Stream. **(b)** Map of subsurface pathways from Lagrangian drifters (Bower, pers. comm.). Color shows the normalized temperature anomaly relative to the float's initial temperature. These 2-year trajectories of RAFOS floats in the subpolar North Atlantic show how they almost exclusively leave the deep boundary-intensified southward current, and instead recirculate in the interior basin. **(c)** Velocity at 200 dbar (red) and 1500 dbar (blue) from electric field profiling floats in a topographically-induced meander of the Antarctic Circumpolar Current, with branches of the Antarctic Circumpolar Current from concurrent satellite altimetry shown as dashed lines (Phillips, pers. comm.). Note how vertical shear varies consistently for cyclonic (marked "C") and anticyclonic (marked "A") curvature, and how surface fronts are often crossed by deep trajectories.

Point Sensors

Point sensors are typically installed on moorings that sample regional circulation. Mooring designs have great variety depending on the research focus, and are even possible on moving sea-ice (Cole et al., 2015). When many moorings are collected into databases (**Figure 2B**), they provide high temporal resolution velocity that are suitable for additional purposes, from scientific (e.g., Wunsch, 1997) to societal (tracking deep oil spills in the Gulf of Mexico, e.g., Hamilton et al., 2011).

Motional Induction

Horizontal water velocity is obtainable by measuring oceanic electric fields caused by salt ions moving through the Earth's magnetic field (Sanford, 1971). The relation between velocity and electric field is simple and provides a near instantaneous response anywhere in the water column. Electric field measurements are possible from multiple platforms (see review by Szuts, 2012): fixed sensors give time-series of depth-averaged velocity (Meinen et al., 2002) or transport (Larsen and Sanford, 1985; Szuts and Meinen, 2013), while implementation on expendable (Sanford et al., 1982) or multicycle profiling floats (Sanford et al., 2007; Kilbourne and Girton, 2015) provides vertical profiles of horizontal velocity. Example data in the Southern Ocean (**Figure 1c**; Phillips and Bindoff, 2014), shows how vertical shear in the Antarctic Circumpolar Current varies with meander curvature, and how surface streamlines identified by fronts are often crossed by deep trajectories.

Existing Sustained Programs That Measure Ocean Velocity

There are three categories of platforms onto which velocity sensors can be mounted: fixed in space (Eulerian), drifting with currents (Lagrangian), or self propelling. There are a few existing velocity sampling networks that are formed by a distributed array of similar platforms.

Shipboard ADCP Records

Oceanographic vessels are outfitted with sADCPs as standard instrumentation, and many countries archive measurements made from their research vessels. For the United States UNOLS

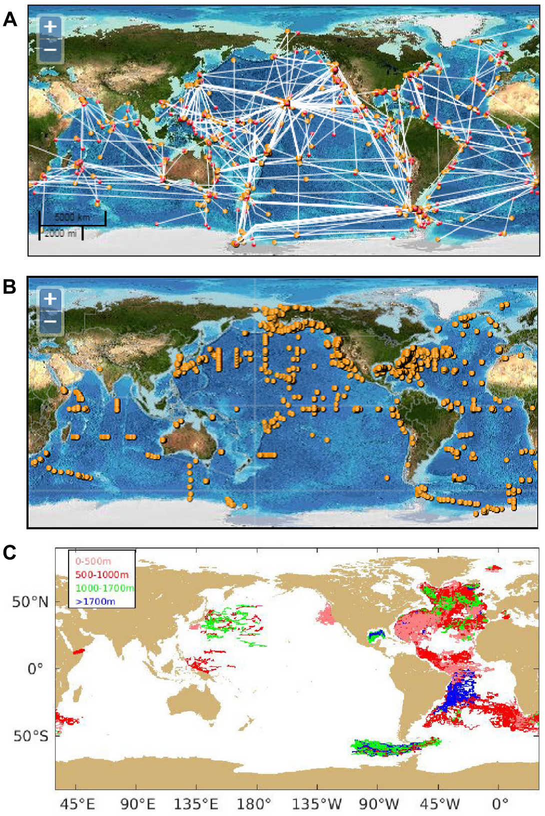

FIGURE 2 | Data available from two recently created archives (see text). From the NOAA National Centers for Environmental Information (NCEI) Global Ocean Currents Database (GOCD), two screen shots show **(A)** shipboard ADCP data (which includes data from the Joint Archive for Shipboard Acoustic Doppler Current Profiler Data, JASADCP; and the Rolling Deck to Repository, (R2R, funded by the National Science Foundation and the Office of Naval Research), and **(B)** mooring data. **(C)** Trajectories of RAFOS floats from the WOCE Subsurface Float Data Assembly Center, updated through December 2017. Colors indicate depth (legend in upper left).

fleet, data acquisition and automated preliminary processing is performed by the UHDAS program from the University of Hawaii. This system provides near real-time ocean currents for scientific and operational use at sea. If this dataset is subsequently manually calibrated and edited, the final data product can be submitted to the Joint Archive for Shipboard Acoustic Doppler Current Profiler Data (JASADCP), a repository for science-ready sADCP data.

Commercial vessels can also be outfitted with sADCP sensors for making measurements along their frequently repeated tracks. The oldest sustained program is a line from New Jersey to Bermuda using the commercial cargo vessel MV *Oleander* (Flagg et al., 1998; Rossby et al., 2010, 2014), which collects transects across the Gulf Stream. These data are well suited for validating models, and show (**Figure 1a**) that velocity variability across the Gulf Stream is highest on the flanks and is directed toward the center.

Other instrumented commercial vessels include cruise ships in the Caribbean (Rousset and Beal, 2010) and ferries and cargo vessels in the North Atlantic and Nordic Seas (Rossby and Flagg, 2012). Instrumenting additional commercial vessels with sADCPs would expand repeat sampling of upper ocean velocity. Additional insight can be added to such systems by expendable temperature probes (Goni et al., 2014), especially if deployed adaptively based on sADCP measurements (Rossby et al., 2011), or by adding collocated meteorological, surface ocean, and biological measurements (OceanScope, 2012).

Mooring Database

Collecting many mooring records together enables new consideration of measurements that are often collected for a specific regional purpose. One database is provided by Oregon State University[1], while some long-duration programs serve data on their own sites (e.g., the 26°N RAPID Overturning Array[2]) or on national servers. Included in this category are mooring programs that maintain arrays intended for measuring ocean transport through a combination of velocity and density measurements (e.g., RAPID, OSNAP[3], Agulhas System Climate Array[4]), or other techniques (Florida Current transport from cable voltages[5]). A sustained global array of equatorial moorings (TAO/TRITON, PIRATA, RAMA), supported by multi-national collaborations and publicly available[6], is especially important to understand non-geostrophic equatorial currents and for model validation (e.g., Kessler et al., 2003).

Argo Network of Drifting Profiling Floats

Although primarily a system for measuring temperature and salinity profiles (Riser et al., 2016), the profiling floats used by Argo measure Lagrangian displacement at 1000 m over 10 days. Argo drift velocities are available from the YoMaHa'07 database (Lebedev et al., 2007), which is now regularly updated and publicly available[7]. It is based on Argo data from the Global Data Assembly Center (GDAC)[8]. Detailed quality control and gridding of drift velocities are available from multiple sources (G-YoMaHa, Katsumata and Yoshinari, 2010; ANDRO, Ollitrault and Rannou, 2013; GADV, Gray and Riser, 2014).

Subsurface Float Drifts

Lagrangian tracks of RAFOS-style float trajectories from many regional studies are now archived and publicly available (Ramsey et al., 2018). Originally compiled by the WOCE Subsurface Float Data Assembly Center in Woods Hole, this comprehensive database is now maintained by NOAA/AOML[9]. Float positions are typically at a temporal resolution of 12 h. As of the latest update (December 2017), the database had trajectories from 2,193 unique floats, half above 1000 dbar and spanning 1972–2015.

[1] http://kepler.oce.orst.edu/
[2] http://www.rsmas.miami.edu/users/mocha
[3] https://www.o-snap.org
[4] https://beal-agulhas.rsmas.miami.edu/research/projects/asca/index.html
[5] http://www.aoml.noaa.gov/phod/floridacurrent/index.php
[6] https://www.pmel.noaa.gov/gtmba/
[7] http://apdrc.soest.hawaii.edu/projects/Argo/data/trjctry
[8] http://www.coriolis.eu.org or http://www.usgodae.org/argo
[9] http://www.aoml.noaa.gov/phod/float_traj

Another data repository for subsurface floats can be found at the PANGAEA data repository[10].

RECOMMENDATIONS FOR INCREASED SOCIETAL USE OF OCEAN CURRENTS

Direct measurements of ocean velocity provide insight into the ocean that can aid societal decisions in many domains to respond to and manage the ocean environment. There is a strong need for improving communication pathways and building dissemination infrastructure to bring together researchers and end users.

Potential End User Applications

Although ocean circulation is fundamental to many societal users of the marine environment, ease of use and applicability are critical for end users to be able to use velocity measurements. Developing derived products for specific applications will require joint discussion between communities.

Similar to other types of observations, velocity observations have clear uses with numerical models. The simplest use is for model validation, to quantify and improve how well models represent the real ocean. Validation can extend beyond mean velocity to include velocity variability, for example to test whether a known subsurface maximum of eddy kinetic energy is reproduced. This is similar to diagnosing Gulf Stream separation latitude based on surface maps of eddy kinetic energy. More formalized use, such as through assimilation into models (Taillandier et al., 2006), will need large advances in understanding velocity structures in space and time, or increased sampling density. One example of model improvement comes from tropical cyclone studies, where measuring the ocean response to winds with electromagnetic velocity profilers (expendable and multi-cycle) enabled an improved parameterization of wind input of momentum that has increased the skill of coupled model forecasts (Shay and Jacob, 2006; Sanford et al., 2011). The Global Drifter Program (GDP, Lumpkin et al., 2016a,b) found that derived products like monthly-averaged maps are often preferred by modelers. Once data are accessible from a single source, then derived products with more uniform spatial or temporal information will be easier to create.

Another use of ocean velocity sampling is to relate remote sensing measurements to subsurface structure (e.g., Chiswell, 2016). This is necessary now for coastal high frequency radar that measures surface currents (Paduan et al., 2004) and for satellite measurements of sea surface height, temperature, or salinity. Though global surface maps have a wide range of applications, fully understanding the subsurface ocean requires measurements in the water column. Tying subsurface velocity to surface conditions will be especially important for upcoming and proposed satellite missions that will sample the ocean at submesoscales (SWOT, US NASA/French CNES) and will potentially provide direct measurements of surface velocities (SKIM from the European Space Agency, Ardhuin et al., 2018; or WaCM from NASA in the United States of America, Chelton et al., 2018).

Data Access

The first step for broader use of velocity observations is better visibility and accessibility. Improving data processing and data management should receive dedicated and systematic support from funding agencies and institutions. The infrastructure for disseminating ocean velocity should be developed now, so that new and emerging capabilities to measure subsurface velocity can be fully utilized as soon as they become available.

Much progress has been made toward this goal through two newly released databases that deserve wider awareness in our community. The United States NOAA National Centers for Environmental Information (NCEI) released a Global Ocean Current Database (GOCD)[11] on 21 July 2015 (Sun, 2018). The database includes measurements from shipboard ADCPs and current meter moorings, and has developed archiving formats and quality control procedures (Sun, 2015). Screen shots of coverage maps for two instrument categories (**Figures 2A,B**) show higher density near coasts and in the northern hemisphere. The GOCD has also created archive-ready velocity file formats suitable for many platforms and sensors. A second database, also released in the past year, archives subsurface float tracks (Ramsey et al., 2018; see description in section "Data Access"). Although studies with acoustically tracked floats have predominantly been done in the Atlantic Basin (**Figure 2C**) to study regional circulation, the compilation of these data now permits additional studies, from comparative analyses to basin-wide model validation studies. Additional work is needed, however, to cover more velocity sampling programs, create archiving standards for all types of velocity measurements, and, ideally, provide a common access point.

In addition to the two active subsurface velocity databases above, our suggestions are informed by the experience of two databases for surface velocity, the NOAA Global Drifter Program[12] that uses low-cost GPS-tracked surface drifters (Lumpkin et al., 2016b), and a network of coastal radars for surface velocity as part of the U.S. Integrated Ocean Observing System[13]. Though these two programs only sample the surface, their data dissemination strategies and user groups provide positive examples.

Limitations of Present-Day Velocity Sampling

Without an easy way to summarize all present sampling, it is hard to evaluate coverage of existing programs and fill potential holes in global sampling. The coverage maps (**Figure 2**) highlight

[10]https://www.pangaea.de

[11]https://www.nodc.noaa.gov/gocd/index.html

[12]http://www.aoml.noaa.gov/phod/gdp/index.php

[13]https://hfradar.ioos.us

the limited sampling outside of the northern hemisphere and Atlantic basin. Temporal coverage is also necessary to resolve seasonal patterns or high frequency variability that impact net fluxes or transports. The community should use existing technologies and platforms to fill these gaps in the short term, coordinated through existing or new sampling programs. Possibilities include collecting ADCP measurements from autonomous vehicles, expanding partnerships with the merchant marine community, deploying velocity profiling floats globally for long duration missions, or sampling subsurface connectivity with tracked Lagrangian floats. In the long term, we must identify new technologies, cost savings, or implementations that increase data return.

SUMMARY OF RECOMMENDATIONS

This article aims to increase use of subsurface ocean velocity measurements beyond their originating community to meet societal needs. The recommendations above fall into three broad categories:

Provide Centralized Access

- Improve visibility and accessibility of existing programs through a common access point
- Contribute, archive and disseminate data from centralized database (e.g., NCEI GOCD)
- Develop data repository standards and format converters for common methods of measuring velocity

Identify and Meet Users Needs

- Define end-user requirements for data formats
- Identify derived products through discussion with potential users. Examples uses include assimilation for numerical models, combining multiple data sets for model validation, interpreting surface satellite observations, or using profiler measurements to improve coupled models that forecast storm events.

Support Data Management and Improve Sampling

- Provide funding and institutional support for data management
- With collaborating agencies, develop data servers, data formats, format converters, and meta-data standards
- Fill observational gaps and improve spatial coverage of velocity sampling
- Apply existing technologies to fill gaps in global coverage in the short term
- Develop technology to increase velocity sampling rates, through cheaper platforms, cheaper sampling networks, or increased data return resulting from more sensor power and/or longer platform lifetimes
- Increase the amount of velocity sampling, for instance by reducing costs (of platforms, networks), improving sensors, or extending vehicle lifetimes.

We encourage scientists, research institutions, and funding agencies to support the actions above in a systematic way to improve our understanding and stewardship of the marine environment.

AUTHOR CONTRIBUTIONS

ZBS conceived and organized the study. ZBS, ASB, KAD, JBG, JMH, KK, RL, PBO, HEP, HTR, LKS, CS, and RET contributed to their area of expertise and to the writing and organization of the article as a whole.

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REFERENCES

Ardhuin, F., Aksenov, Y., Benetazzo, A., Bertino, L., Brandt, P., Caubet, E., et al. (2018). Measuring currents, ice drift, and waves from space: the sea surface kinematics multiscale monitoring (skim) concept. *Ocean Sci.* 14, 337–354. doi: 10.5194/os-14-337-2018

Bower, A. S., Lozier, M. S., Gary, S. F., and Böning, C. W. (2009). Interior pathways of the North Atlantic meridional overturning circulation. *Nature* 459, 243–247. doi: 10.1038/nature07979

Chamberlain, P., Talley, L. D., Mazloff, M. R., Riser, S., Speer, K., Gray, A. R., et al. (2018). Observing the ice-covered weddell gyre with profiling floats: position uncertainties and correlation statistics. *J. Geophys. Res. Oceans* 123, 8383–8410. doi: 10.1029/2017JC012990

Chelton, D. B., Schlax, M. G., Samelson, R. M., Farrar, J. T., Molemaker, J., McWilliams, J. C., et al. (2018). Prospects for future satellite estimation of small-scale variability of ocean surface velocity and vorticity. *Prog. Oceanogr.* 173, 256–350. doi: 10.1016/j.pocean.2018.10.012

Chiswell, S. M. (2016). Mean velocity decomposition and vertical eddy diffusivity of the pacific ocean from surface gdp drifters and 1000-m argo floats. *J. Phys. Oceanogr.* 46, 1751–1768. doi: 10.1175/JPO-D-15-0189.1

Cole, S. T., Thwaites, F. T., Krishfield, R. A., and Toole, J. M. (2015). "Processing of velocity observations from ice-tethered profilers," in *Proceedings of the MTS/IEEE Oceans 2015 Conference*, Washington, DC.

Fischer, J., and Visbeck, M. (1993). Deep velocity profiling with self-contained ADCPs. *J. Atmos. Oceanic. Technol.* 10, 764–773. doi: 10.1175/1520-0426(1993)010<0764:dvpwsc>2.0.co;2

Flagg, C. N., Schwartze, G., Gottlieb, E., and Rossby, T. (1998). Operating an acoustic doppler current profiler aboard a container vessel. *J. Atmosp. Ocean. Tech.* 15, 257–271. doi: 10.1175/1520-0426(1998)015<0257:oaadcp>2.0.co;2

Gill, A. E. (1982). *Atmosphere-Ocean Dynamics of International Geophysics Series*, Vol 30. San Diego, CA: Academic Press.

Goni, G., Sprintall, J., Roemmich, D.,Gronell, A., Thresher Couley, R., and Baringer, M. (2014). "The global network of XBT temperature sections in support of oceanographic and climate studies," in *Oceans and Society: Blue Planet*, ed. S. Djavidnie (Cambridge: Cambridge Scholars Publishing).

Gray, A. R., and Riser, S. C. (2014). A global analysis of sverdrup balance using absolute geostrophic velocities from argo. *J. Phys. Oceanogr.* 44, 1213–1229. doi: 10.1175/JPO-D-12-0206.1

Guerra, M., and Thomson, J. (2017). Turbulence measurements from five-beam acoustic doppler current profilers. *J. Atmos. Ocean. Technol.* 34, 1267–1284. doi: 10.1175/JTECH-D-16-0148.1

Hamilton, P., Donohue, K., Leben, R. R., Lugo-Fernández, A., and Green, R. (2011). "Loop current observations during spring and summer of 2010: description and historical perspective," in *Monitoring and Modeling the Deepwater Horizon Oil Spill: A Record-breaking Enterprise*. eds Y. Liu, A. MacFadyen and Z. G. J. R. Weisberg (American Geophysical Union: Washington, DC), 117–130. doi: 10.1029/2011gm001116

Katsumata, K., and Yoshinari, H. (2010). Uncertainties in global mapping of argo drift data at the parking level. *J. Oceanogr.* 66, 553–5691. doi: 10.1007/s10872-010-0046-4

Kessler, W. S., Johnson, G. C., and Moore, D. W. (2003). Sverdrup and nonlinear dynamics of the Pacific equatorial currents. *J. Phys. Oceanogr.* 33, 994–1008. doi: 10.1175/1520-0485(2003)033<0994:sandot>2.0.co;2

Kilbourne, F. B., and Girton, J. B. (2015). Quantifying high-frequency wind energy flux into near-inertial motions in the southeast Pacific. *J. Phys. Oceanogr.* 45, 369–386. doi: 10.1175/jpo-d-14-0076.1

Larsen, J. C., and Sanford, T. B. (1985). Florida current volume transport from voltage measurements. *Science* 227, 302–304. doi: 10.1126/science.227.4684.302

Lebedev, K., Yoshinari, H., Maximenko, N. A., and Hacker, P. W. (2007). YoMaha'07: velocity data assessed from trajectories fo argo floats at parking level and at the sea surface. *IPRC Tech.* 4:6.

Levine, E. R., Connors, D. N., Cornillon, P. C., and Rossby, H. T. (1986). Gulf stream kinematics along an isopycnal float trajectory. *J. Phys. Oceanogr.* 16, 1317–1328. doi: 10.1175/1520-0485(1986)016<1317:gskaai>2.0.co;2

Lumpkin, R., Centurioni, L., and Perez, R. C. (2016a). Fulfilling observing system implementation requirements with the global drifter array. *J. Atmos. Oceanic Technol.* 33, 685–695. doi: 10.1175/JTECH-D-15-0255.1

Lumpkin, R., Ozgokmen, T., and Centurioni, L. (2016b). Advances in the applications of surface drifters. *Annu. Rev. Mar. Sci.* 9, 59–81. doi: 10.1146/annurev-marine-010816-060641

MacKinnon, J. A., Alford, M. H., Ansong, J. K., Arbic, B. K., Barna, A., Briegleb, B. P., et al. (2017). Climate process team on internal wave-driven ocean mixing. *Bull. Am. Meteorol. Soc.* 98, 2429–2454. doi: 10.1175/BAMS-D-16-0030.1

Meinen, C. S., Luther, D. S., Watts, D. R., Tracey, K. L., Chave, A. D., and Richman, J. (2002). Combining inverted echo sounder and horizontal electric field recorder measurements to obtain absolute velocity profiles. *J. Atmos. Oceanic Technol.* 19, 1653–1664. doi: 10.1175/1520-0426(2002)019<1653:ciesah>2.0.co;2

OceanScope (2012). "A Proposed Partnership Between the Maritime Industries and the Ocean Observing Community to Monitor the Global Ocean Water Column," in *Report of SCOR/IAPSO Working Group 133*, eds T. Rossby and K. Kim (Paris: SCOR/IAPSO Final Report).

Ollitrault, M., and Rannou, J.-P. (2013). ANDRO: an Argo-based deep displacement dataset. *J. Atmos. Ocean. Technol.* 30, 759–788. doi: 10.1175/JTECH-D-12-00073.1

Paduan, J. D., Kosro, P. M., and Glenn, S. M. (2004). A national coastal ocean high frequency radar system for the United States. *Mar. Tech. Soc. J.* 38, 76–82.

Pedlosky, J. P. (1979). *Geophysical Fluid Dynamics*. Berlin: Springer-Verlag.

Phillips, H. E., and Bindoff, N. L. (2014). On the non-equivalent barotropic structure of the antarctic circumpolar current: an observational perspective. *J. Geophys. Res. Oceans* 119, 5221–5243. doi: 10.1002/2013JC009516

Ramsey, A. L., Furey, H. H., and Bower, A. S. (2018). Deep floats reveal complex ocean circulation patterns. *Eos* 99 doi: 10.1029/2018EO105549

Reid, J. L. (1994). On the total geostrophic circulation of the north atlantic ocean: flow patterns, tracers, and transports. *Prog. Oceanogr.* 33, 1–92. doi: 10.1016/0079-6611(94)90014-0

Richardson, P. L. (2018). "Drifters and floats," in *Encyclopedia of Ocean Sciences* eds K. Turekian, S. A. Thorpe, and J. Steele. Woods Hole, MA: Woods Hole Oceanographic Institution.

Riser, S. C., Freeland, H. J., Roemmich, D., Wijffels, S., Troisi, A., Belbéoch, M., et al. (2016). Fifteen years of ocean observations with the global argo array. *Nat. Clim. Change* 6, 145–153.

Rossby, H. T., Dorson, D., and Fontaine, J. (1986). The RAFOS system. *J. Atmosp. Ocean. Technol.* 3, 672–679. doi: 10.1175/1520-0426(1986)003<0672:trs>2.0.co;2

Rossby, T., Flagg, C., and Donohue, K. (2010). On the variability of gulf stream transport from seasonal to decadal timescales. *J. Mar. Res.* 68, 503–522. doi: 10.1357/002224010794657128

Rossby, T., Flagg, C., Ortner, P., and Hu, C. (2011). A tale of two eddies: diagnosing coherent eddies through acoustic remote sensing. *J. Geophys. Res.* 116:C12017. doi: 10.1029/2011JC007307

Rossby, T., and Flagg, C. N. (2012). Direct measurement of volume flux in the faroe-shetland channel and over the iceland-faroe ridge. *Geophys. Res. Lett.* 39:L07602.

Rossby, T., Flagg, C. N., Donohue, K., Sanchez-Franks, A., and Lillibridge, J. (2014). On the long-term stability of Gulf Stream transport based on 20 years of direct measurements. *J. Geophys. Res.* 41, 114–120. doi: 10.1002/2013gl058636

Rossby, T., and Özgökmen, T. (2007). "Evolution of lagrangian methods in oceanography," in *Lagrangian Analysis and Prediction of Coastal and Ocean Dynamics*, eds A. Griffa, A. D. Kirwan Jr., A. JMariano, and H. T. Rossby (Cambridge: Cambridge Univ. Press).

Rousset, C., and Beal, L. M. (2010). Observations of the yucatan and florida currents from caribbean cruise ship. *J Phys. Oceanogr.* 40, 1575–1581. doi: 10.1175/2010jpo4447.1

Sanford, T. B. (1971). Motionally induced electric and magnetic fields in the sea. *J. Geophys. Res. Oceans* 76, 3476–3492. doi: 10.1029/JC076i015p03476

Sanford, T. B., Drever, R. G., Dunlap, J. H., and D'Asaro, E. A. (1982). *Design, Operation, and Performance of an Expendable Temperature and Velocity Profiler (XTVP)*. Seattle, WA: University of Washington.

Sanford, T. B., Price, J. F., and Girton, J. B. (2011). Upper-ocean response to Hurricane Frances (2004) observed by profiling EM-APEX floats. *J. Phys. Oceanogr.* 41 1041–1056. doi: 10.1175/2010JPO4313.1

Sanford, T. B., Price, J. F., Girton, J. B., and Webb, D. C. (2007). Highly resolved observations and simulations of the ocean response to a hurricane. *Geophys. Res. Lett.* 34:L13604.

Shay, L. K., and Jacob, S. D. (2006). "Relationship between oceanic energy fluxes and surface winds during tropical cyclone passage" in *Atmosphere-Ocean Interactions II, Advances in Fluid Mechanics* ed. W. Perrie (Southampton: WIT Press), 115–142. doi: 10.2495/978-1-85312-929-2/05

Sun, C. (2015). *Reference Manual for Quality Control of Subsurface Currents Data (QCSCD)*. Available at: https://www.nodc.noaa.gov/gocd/documents/qcscd_manual_v1.pdf (accessed March 21, 2019).

Sun, C. (2018). *US DOC/NOAA/NESDIS National Centers for Environmental Information NCEI Standard Product: Global Ocean Currents Database (GOCD)*. NOAA: Silver Spring.

Szuts, Z. B. (2012). Using motionally-induced electric fields to indirectly measure ocean velocity: instrumental and theoretical developments. *Prog. Oceanogr.* 96, 108–127. doi: 10.1016/j.pocean.2011.11.014

Szuts, Z. B., and Meinen, C. S. (2013). Salinity transport in the florida straits. *J. Atmos. Ocean. Technol.* 30, 971–983. doi: 10.1175/jtech-d-12-00133.1

Taillandier, V., Griffa, A., Poulain, P. M., and Béranger, K. (2006). Assimilation of argo float positions in the north western mediterranean sea and impact on ocean circulation simulations. *Geophys. Res. Lett.* 33:L11604. doi: 10.1029/2005GL025552

Thomson, J., and Girton, J. (2017). Sustained measurements of southern ocean air-sea coupling from a wave glider autonomous surface vehicle. *Oceanography* 30, 104–109. doi: 10.5670/oceanog.2017.228

Todd, R. E., Rudnick, D. L., Sherman, J. T., Owens, W. B., and George, L. (2017). Absolute velocity estimates from autonomous underwater gliders equipped with doppler current profilers. *J. Atmos. Ocean. Technol.* 34, 309–333. doi: 10.1175/JTECH-D-16-0156.1

Uhlhorn, E. W., and Shay, L. K. (2012). Loop current mixed layer energy response to hurricane lili (2002). Part I: observations. *J. Phys. Oceanogr.* 42, 400–419. doi: 10.1175/jpo-d-11-096.1

Wunsch, C. (1997). The vertical partition of oceanic horizontal kinetic energy. *J. Phys. Oceanogr.* 27, 1770–1794. doi: 10.1175/1520-0485(1997)027<1770:tvpooh>2.0.co;2

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frontiers in Marine Science

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The International Comprehensive Ocean-Atmosphere Data Set – Meeting Users Needs and Future Priorities

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The International Comprehensive Ocean-Atmosphere Data Set (ICOADS) is a collection and archive of *in situ* marine observations, which has been developed over several decades as an international project and recently guided by formal international partnerships and the ICOADS Steering Committee. ICOADS contains observations from many different observing systems encompassing the evolution of measurement technology since the 18th century. ICOADS provides an integrated source of observations for a range of applications including research and climate monitoring, and forms the main marine *in situ* surface data source, e.g., near-surface ocean observations and lower atmospheric marine-meteorological observations from buoys, ships, coastal stations, and oceanographic sensors, for oceanic and atmospheric research and reanalysis. ICOADS has developed ways to incorporate user and reanalyses feedback information associated with permanent unique identifiers and is also the main repository for data that have been rescued from ships' logbooks and other marine data digitization activities. ICOADS has been adopted widely because it provides convenient access to a range of observation types, globally, and through the entire marine instrumental record. ICOADS has provided a secure home for such observations for decades. Because of the increased volume of observations, particularly those available in near-real-time, and an expansion of their diversity, the ICOADS processing system now requires extensive modernization. Based on user feedback, we will outline the improvements that are required, the challenges to their implementation, and the benefits of upgrading this important and diverse marine archive and distribution activity.

Keywords: surface, *in situ*, observations, marine meteorology, ocean, climate, data management

ICOADS HISTORY AND COMMUNITY DEVELOPMENT

The International Comprehensive Ocean-Atmosphere Data Set (ICOADS) Release 3 (R3.0) is the largest collection of surface marine observations spanning from 1662 to the present day (Freeman et al., 2017). The dataset is a collection of environmental observations from a range of marine observing platforms as shown in **Figure 1**. Many of the data originate from ships, but since the 1970s buoys and other platforms began to emerge and gain popularity in the observing system.

The original COADS was released in 1985 (Slutz et al., 1985) providing open access to individual reports from the surface marine climate record for the first time. Observations include a range of surface Essential Climate Variables (ECVs) and Essential Ocean Variables (EOVs) (Bojinski et al., 2014) from ships, moored and drifting buoys, fixed platforms and other types of measurement platforms. These individual observations underpin gridded monthly climate summary statistics for sea surface temperature (SST), air temperature, humidity, sea level pressure, wind speed and components, and cloud cover. These statistics are produced at 2° and 1° spatial resolution dating back to 1800 and 1960, respectively. The ICOADS summaries have been superseded for most applications by more sophisticated products offering improvements in quality control (QC), treatment of uncertainty, bias adjustment, or statistical infilling of unobserved regions or periods, for specific variables. Such products are the foundation of climate monitoring, for example providing the marine component of estimates of Global Mean Surface Temperature (GMST) that defines the ambition of the UN Framework Convention on Climate Change (UNFCCC) and the resulting Paris Agreement to prevent dangerous climate change (e.g., Huang et al., 2017; Kent et al., 2019). These products are based on ICOADS individual observations because they provide traceable access to data in a uniform format regardless of its source.

The ICOADS has evolved from a United States-centric effort to an international collaboration, emphasizing the 'I' in ICOADS. Since 2014, developments have been guided in partnership between the United States National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Information (NCEI), the National Center for Atmospheric Research (NCAR), the Florida State University (FSU), and internationally with organizations including Deutscher Wetterdienst (DWD, Germany), the National Oceanography Centre (NOC, United Kingdom) and the Met Office (United Kingdom). NOAA/NCEI have responsibility for the day-to-day operation and maintenance of ICOADS and provide basic data access and periodic full updates. NCAR provides enhanced access to ICOADS that supports data subsetting and alternative data formats and provides access to "value-added" data products and metadata. The other partners provide expertise to ICOADS, access to new observations, and *ad hoc* support, e.g., with testing, answering user questions, and documentation.

Since 2017 the European Union Copernicus Climate Change Service has provided funding for the modernization of processing systems for marine climate data (C3S 311a Lot 2: Access to observations from global climate data archives[1]). This has allowed ICOADS partners (NOC and the Met Office) to develop new systems for QC, harmonize and extend metadata and improve duplicate identification for ICOADS observations. In partnership with this activity NCEI have committed to incorporate these improved systems into their ICOADS processing system, requiring a major update to their current processing capability.

The ICOADS was created as an archive focusing on those parameters typically measured by Voluntary Observing Ships (VOS, Smith et al., 2019), and includes only observations made near the surface and contains very limited reports of biogeochemical parameters. Typical sampling intervals depend on the observing platform type and range from hourly to daily. Satellite measurements are outside the scope of ICOADS. The archive has expanded in the past to include measurements using new platform and sensor technologies, and observations at higher frequencies, e.g., 10 or more reports per hour. However, the extent to which ICOADS has the capability to incorporate new types and higher data volumes, emerging or planned, is presently unclear.

Since inception, ICOADS has been shaped and developed by the user community, including through a series of workshops on Advances in Marine Climatology (CLIMAR; JCOMM, 2015) and on the Advances in the Use of Historical Marine Climate Data (MARCDAT; JCOMM, 2016). The fifth session of the CLIMAR series (CLIMAR-5) was hosted by DWD in Hamburg, Germany in May 2019 and discussed and further developed community needs and requirements prior to OceanObs'19.

A FOUNDATIONAL DATABASE

The ICOADS provides access to an archive of surface marine measurements of ECVs and EOVs stretching back to the earliest observations in the late 17th century and have been updated to include data for the latest complete month. ICOADS provides data from a range of different platform types, initially dominated by reports from ships, but now representing a diverse range including different types of buoys, fixed platforms and profilers. Unlike archives for land data that have often separated data by parameter (Thorne et al., 2018), ICOADS has kept multivariate reports together, storing any parameters or metadata that could not be accommodated in the main record in a data supplement.

In addition to the general community of scientists, the primary user groups for ICOADS include dataset developers, reanalysis centers, and the satellite community. Through its use in many data products [e.g., HadSST3 (Kennedy et al., 2011), HadISST (Rayner et al., 2003), ERSSTv5 (Huang et al., 2017), COBE-SST2 (Hirahara et al., 2014), HadNMAT2 (Kent et al., 2013), HadCRUT4 (Morice et al., 2012), MLOST (Vose et al., 2012), NOAAGlobalTemp (Zhang et al., 2019), GISTEMP (Hansen et al., 2010), WASWind (Tokinaga and Xie, 2011), NOCv2.0 (Berry and Kent, 2009), and HadCRUH (Willett et al., 2008)], and as input data

[1] https://climate.copernicus.eu/node/562

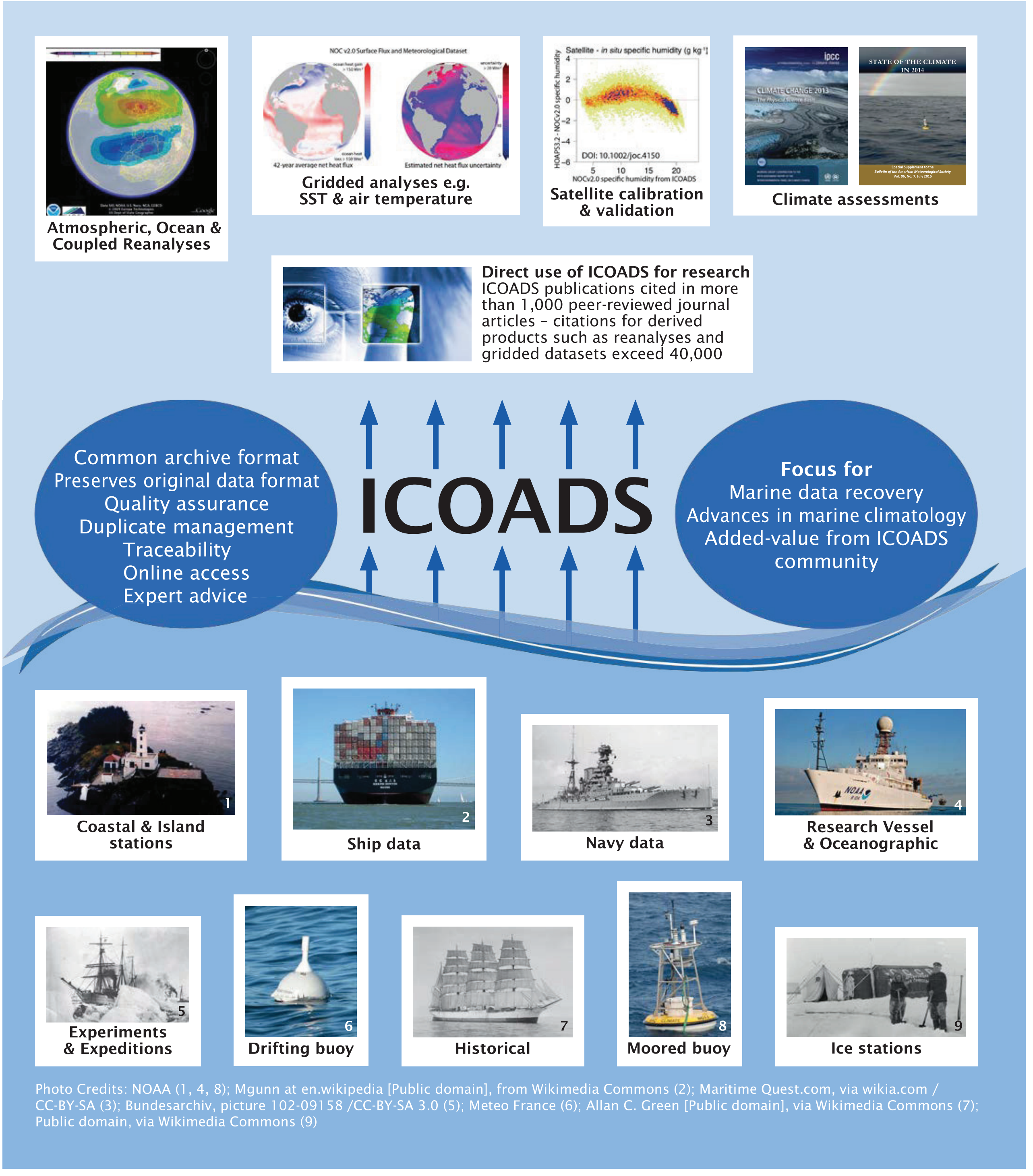

FIGURE 1 | International Comprehensive Ocean-Atmosphere Data Set (ICOADS) processes data from many different platforms that feed into a wide variety of products.

sources for assimilation into atmospheric, oceanic and coupled reanalyses [e.g., The 20th Century Reanalysis (Compo et al., 2011), ERA-Interim (Dee et al., 2011), NCEP CFSR (Saha et al., 2010), SODA (Carton and Giese, 2008), and MERRA (Rienecker et al., 2011)] the impact of ICOADS is greatly amplified. Journal citations for these indirect user groups exceeded 8000 in 2017. Satellite applications include the iQuam *in situ* SST quality monitor (Xu and Ignatov, 2014), evaluation of heat flux products (Prytherch et al., 2015; Kinzel et al., 2016; Liman et al., 2018), and SST assessments (Berry et al., 2018; Tsamalis and Saunders, 2018).

Climate change monitoring and assessment (e.g., Intergovernmental Panel on Climate Change [IPCC], 2013), the State of the Climate report (Blunden and Arndt, 2018), the World Meteorological Organization (WMO) Statement on the State of the Global Climate 2017 (World Meteorological Organization [WMO], 2018) all require climate data records to be updated, typically with the latest complete month or year. ICOADS therefore produces monthly updates based on near real time (NRT) data from the Global Telecommunications System (GTS) to support such users. The current version is R3.0.1, covering 2015 to the present.

Periodically, ICOADS produces new major releases (Slutz et al., 1985; Woodruff et al., 1993, 1998, 2011; Worley et al., 2005; Freeman et al., 2017) which ingest new or improved data sources, update data formats or processing methodology, and may replace some NRT observations with data from selected delayed mode archives. Every ICOADS release has ingested newly available marine observations from data rescue activities and R3.0 saw new data from citizen science initiatives (Old Weather, Weather Detective), the atmospheric circulation reconstructions over the Earth initiative (ACRE, Allan et al., 2011), and from DWD, NCEI, the Australian Bureau of Meteorology, Woods Hole Oceanographic Institute, and Environment Canada. Data from delayed mode archives were updated, including from the world ocean database 2013 (WOD; Boyer et al., 2013); the Global Ocean Surface Underway Data (GOSUD) Project; buoy measurements from the Global Tropical Moored Buoy Array (McPhaden et al., 1998, 2009; Bourlès et al., 2008) and the Canadian Oceanography and Scientific Data archive; and research vessel observations from the Shipboard Automated Meteorological and Oceanographic System (SAMOS) initiative (Smith et al., 2009, 2018). Significant extensions to data formats included a report-level "unique identifier" to support applications with requirements for detailed provenance, and new depth referenced oceanographic data including seawater temperature, salinity, nutrients, oxygen, and dissolved carbon elements from the WOD (Boyer et al., 2013).

DATA ACCESS AND SERVICES

International Comprehensive Ocean-Atmosphere Data Set data products are available from NCEI/NOAA, ESRL/PSD/NOAA and NCAR[2]. NCAR provides access to the products in the native production ASCII International Marine Meteorological Archive (IMMA) format, for individual observations (Smith et al., 2016). This basic access is extended with user interfaces that drive spatial, temporal, and parameter selection data subsetting services, and output formats are provided in tabular and comma-separated-value (CSV) ASCII. Subsetting has numerous additional features that allow users to customize output products, taking advantage of the extensive content in the IMMA format and ICOADS Value-added Database (IVAD). Users are able to select standard or customized QC levels, choose individual parameters and metadata, and receive a full data record provenance in the output. IVAD also has the unique capability to collect feedback from users and to produce a rich history of the observations through the data lifecycle. First, adjusted data values produced and documented by community experts to address sampling and instrumentation biases are provided as supplemental attachments to the core observation records. Second, assimilation feedback information from climate reanalysis projects can be stored in IVAD and includes parameters such as model bias corrections, first-guess values, and QC flags. Both of these elements are provided in the full IMMA records and can also be selected in the subsetting service supported at NCAR.

ON-GOING WORK AND FUTURE REQUIREMENTS

Marine archives rely on observations transmitted in NRT, typically in support of weather forecasting operations. Whilst many national weather prediction centers maintain their own collections of such observations, as there is no formal international system for the archival of and free access to these data. ICOADS has implicitly fulfilled this role for surface marine data, but this is a major task, even for the data types currently supported. A major focus for ICOADS since the production of R3.0.0 (Research Data Archive et al., 2016) has been the transition to the Binary Universal Form for the Representation of Meteorological Data (BUFR) format, used for real-time transmissions on the GTS. A stand-alone dataset of decoded binary format reports for buoys and ships now exists and will be incorporated into a new NRT product in the future, when all format translations are fully validated.

The ICOADS serves users who need access to a broad and diverse range of surface marine observations and takes advantage of the co-location of several ECVs and EOVs with extensive platform and observational metadata. This unified access means that most climate data products are constructed from the same extensive archive, thus any differences between products can be attributed to methodological differences rather than unknown differences in observational input. For users requiring strong data provenance, this is essential, and it also has the advantage of promoting the sharing of information about issues with the data, or exchange of information about processing applied at the report level, including through the construction of formal IVAD additions to the ICOADS record. For ICOADS to continue to serve as the sole or main data source for a wide range of data products it must remain as complete as possible within its defined scope, be reliably and conveniently available, and fully traceable.

One measure of the value of ICOADS is the frequency of calls for it to include a wider range of variables and additional platform types. Fulfilling the needs of users requesting

[2]http://icoads.noaa.gov/products.html

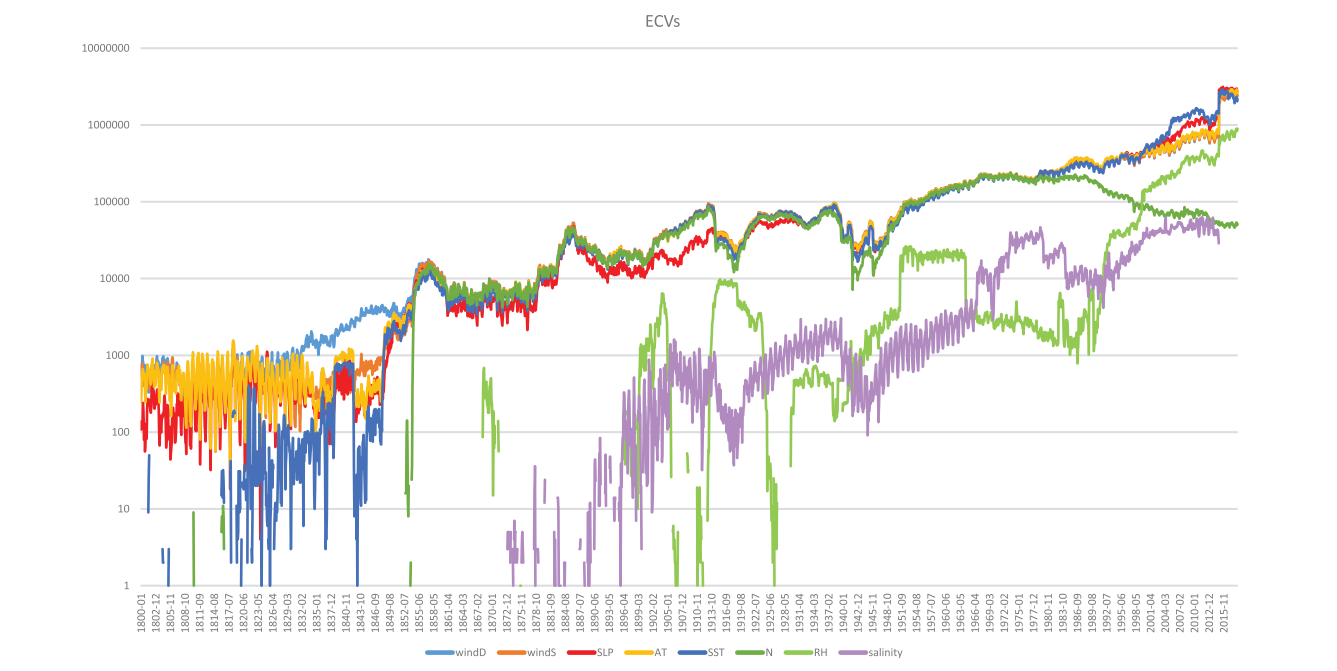

FIGURE 2 | Essential Climate Variables (ECVs) in International Comprehensive Ocean-Atmosphere Data Set (ICOADS) R3.0.0 and R3.0.1 from January 1800 to September 2018: windD, wind direction; windS, wind speed; SLP, sea level pressure; AT, air temperature; SST, sea surface temperature; N, total cloud amount; RH, relative humidity; salinity, sea surface salinity. The *y* axis is in a $\log_{10}$ scale and shows the number of reports per month for those ECVs listed.Some elements are highly variable in their availability, especially in the early period of record. In the modern period there are noticeable decreases in ECVs, i.e., cloud observations and even SST. Some of these, i.e., clouds, are attributed to changes from manual observations to automated observation systems, where humans have not been replaced by sensors to continue observing the parameters.

faster access to NRT data, more frequent full releases, and a wider range of variables and data sources requires a solid, resource-backed commitment. The ability to fulfill these requests is unachievable without sufficient resources for ICOADS and the provision of dedicated, internationally integrated data management systems that can feed marine data into ICOADS.

The ICOADS serves as the archive for the output of marine digitization activities. Producers of long-term reanalyses (e.g., Compo et al., 2011; Poli et al., 2016) require these observations to be quickly incorporated into ICOADS and call for more frequent full release updates to support this facility. Annual or quarterly to semiannual updates have been recommended, and a defined update cycle will help dataset developers plan their own upgrades.

The ICOADS can only be as good as the data sources on which it relies. The decline in numbers, and coverage, of reports of ECVs, as shown in **Figure 2**, has been documented (Kent et al., 2006; Berry and Kent, 2017). This has been a particular problem for the production of long-term datasets of air temperature (Kent et al., 2013), humidity (Willett et al., 2008; Berry and Kent, 2009), clouds (Eastman et al., 2011), winds (Tokinaga and Xie, 2011) and waves (Grigorieva et al., 2017; see Kent et al., 2019 for more information). It is also restricting the development of satellite-derived datasets of parameters critical for estimation of surface heat flux (Kinzel et al., 2016; Liman et al., 2018; Cronin et al., 2019), a newly designated ECV (Global Climate Observing System [GCOS], 2016).

The ICOADS incorporates several delayed mode archives, but each requires extensive processing to conform to the ICOADS data formats. A further task is the identification of data matches between NRT and delayed mode versions of the same original reports, a task made difficult by changes in data format between sources and the lack of unique identifiers to cleanly identify and flag different versions of the same original data.

Extension of ICOADS to new data types (e.g., Autonomous Surface Vehicles, ASVs), or to a wider range of oceanographic data types, will need to be supported by dedicated data management systems for those specific data types. Each different type of data source requires a data system designed for its needs with evaluation by experts. New data systems will need to be compliant with WMO Integrated Global Observing System (WIGOS) technical regulations[3]. Recent work at NCEI, to enable translation of BUFR codes for ICOADS, will need to be extended and the IMMA format used by ICOADS will require updating to align with the new standards more closely.

There also have been calls for a full reprocessing of the ICOADS archive (e.g., Kent et al., 2017). The early releases

[3]http://www.wmo.int/pages/prog/www/wigos/WRM.html

of ICOADS (Woodruff et al., 1987, 1993, 1998; Worley et al., 2005) did not retain observations thought to be inferior duplicates through the processing system. These data, up to a third of the total, are only available in deprecated data formats. Recovery of these data will provide information on uncertainty due to different data processing paths and provide examples and training data for the identification of inexact duplicates. This will enable improved duplicate flagging within ICOADS, and permit users to develop their own schemes. Recovery and reprocessing of existing ICOADS sources will also facilitate the enhancement of ICOADS platform metadata through ship tracking (Carella et al., 2017), needed for advanced approaches to uncertainty estimation (Kennedy, 2014; Kent et al., 2017).

In order for ICOADS to remain the central repository for surface *in situ* marine data, many updates are needed in order to modernize the source data, the underlying processing system, and to better address community needs in an efficient and timely manner. ICOADS will engage users directly through workshops and user surveys, as well as coordinate tasks with international partners and programs, leveraging existing expertise and resources. To do this, a solid foundation is needed at the hosting center, including a dedicated team tasked specifically to these duties. The following recommendations have been proposed, and where possible are being acted upon. A complete modernization, building on current features, is overdue. OceanObs'19 provides a large venue to gain a broader perspective of the needs of the marine community, setting the groundwork to expand on and include new community recommendations. ICOADS is committed to meeting users' needs and plan to incorporate the following recommendations with the guidance of partners, data set users, and the OceanObs'19 community.

RECOMMENDATIONS

Maintain the Best Features of the Present ICOADS Data System

Continue to provide open and free access to the most complete archive of surface marine observations, with NRT updates and periodic ingestion of new observations.

Continue to support users with traceable and reproducible data, including for custom subsets that can be formally cited in publications.

Continue to work closely with the marine data rescue community in acting as the principle archive for newly digitized or recovered surface marine observations, ensuring that ICOADS adapt to capture and make accessible diverse information from historical digitization.

Modernization of ICOADS

The ICOADS data systems require modernization to align with current international format and metadata standards more closely, such as WIGOS. This will enable efficient future ingestion of WIGOS-compliant data sources, especially in NRT BUFR streams.

The ICOADS processing needs to be restructured into a modular system to easily allow the development and testing of new code, to integrate improved software from external sources such as Copernicus C3S 311a. ICOADS has always been open source, but now requires a modern code management system that supports community code development.

Improved approaches to QC and duplicate identification should be implemented along with flexible access to data with different levels of QC flagging.

Support user needs for higher levels of traceability, for example linking rescued data directly to logbook images.

Review all data sources, including original inputs to early releases, and the available delayed mode archives and NRT streams to ensure that ICOADS is based on the best data sources.

Facilitate community involvement in reprocessing in addition to data rescue efforts.

Improve the completeness of ICOADS documentation and provide simpler access to the wide variety of supporting information underlying that documentation. Continue to work with the data rescue community to digitize documentation and metadata for existing data sources.

Improving Integration of ICOADS With International Data Systems

Formalizing ICOADS Internationally: Fulfill role as Centre for Marine-Meteorological and Oceanographic Climate Data (CMOC) in the JCOMM Marine Climate Data System (MCDS) (see World Meteorological Organization [WMO] (2017a,b); Pinardi et al. (2019) for more information on the JCOMM MCDS). By serving in this capacity, ICOADS will integrate more formally with international data systems and provide enhancements to global data management and quality.

Improve resilience of ICOADS data, processes, and documentation by providing automated mirroring at ICOADS partner sites in order to avoid disruptions of service and to provide backups in case of technological failure and unexpected down time of ICOADS main operational systems hosted at NCEI. Mirroring will also satisfy a CMOC requirement when operating in the MCDS international data management system.

Improve collaboration with experts providing access to delayed mode data archives to provide this enhanced data more efficiently to ICOADS users. Work to ensure that all contributions to ICOADS are explicitly recognized in data citations.

Requirements for Enhancements to Global Data Management Systems

Establish centers responsible for the secure archival of NRT marine observations from the GTS in their native formats.

Building on the successful examples, such as the Argo Data System (ASVs)[4], establish international data centers for all marine observation types including for ASVs to ensure that all new data types are managed by domain experts and can be efficiently integrated into more general archives such as ICOADS.

[4] www.argodatamgt.org

Work with data providers to establish the inclusion of originators unique identification tags with all marine observations to enable the efficient linking of reports derived from the same original observation.

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CL, EK, and LG developed and contributed the figures. All authors contributed to writing sections of the manuscript and each read and approved its final version.

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REFERENCES

Allan, R., Brohan, P., Compo, G. P., Stone, R., Luterbacher, J., and Brönnimann, S. (2011). The international atmospheric circulation reconstructions over the earth (ACRE) initiative. *Bull. Am. Meteorol. Soc.* 92, 1421–1425. doi: 10.1175/2011BAMS3218.1

Berry, D. I., Corlett, G., Embury, O., and Merchant, C. (2018). Stability assessment of the (A)ATSR sea surface temperature climate dataset from the european space agency climate change initiative. *Remote Sens.* 10:126. doi: 10.3390/rs10010126

Berry, D. I., and Kent, E. C. (2009). A new air-sea interaction gridded dataset from ICOADS with uncertainty estimates. *Bull. Am. Meteorol. Soc.* 90, 645–656. doi: 10.1175/2008BAMS2639.1

Berry, D. I., and Kent, E. C. (2017). Assessing the health of the global surface marine climate observing system. *Int. J. Climatol.* 37, 2248–2259. doi: 10.1002/joc.4914

Blunden, J., and Arndt, D. S. (eds) (2018). State of the climate in 2017. *Bull. Am. Meteorol. Soc.* 99, Si–S332. doi: 10.1175/2018BAMSStateoftheClimate.1

Bojinski, S., Verstraete, M., Peterson, T. C., Richter, C., Simmons, A., and Zemp, M. (2014). The concept of essential climate variables in support of climate research, applications, and policy. . *Bull. Am. Meterol. Soc.* 95, 1431–1443. doi: 10.1175/BAMS-D-13-00047.1

Bourlès, B., Lumpkin, R., McPhaden, M. J., Hernandez, F., Nobre, P., Campos, E., et al. (2008). The PIRATA program: history, accomplishments, and future directions. *Bull. Am. Meteorol. Soc.* 89, 1111–1125. doi: 10.1175/2008BAMS2462.1

Boyer, T. P., Antonov, J. I., Baranova, O. K., Coleman, C., Garcia, H. E., Grodsky, A., et al. (2013). *World Ocean database 2013*, eds S. Levitus and A. Mishonov (Silver Spring, MD: NOAA Atlas NESDIS), 209. doi: 10.7289/V5NZ85MT

Carella, G., Kent, E. C., and Berry, D. I. (2017). A probabilistic approach to ship voyage reconstruction in ICOADS. *Int. J. Climatol.* 37, 2233–2247. doi: 10.1002/joc.4492

Carton, J. A., and Giese, B. S. (2008). A reanalysis of ocean climate using simple ocean data assimilation (SODA). *Mon. Wea. Rev.* 136, 2999–3017. doi: 10.1175/2007MWR1978.1

Compo, G. P., Whitaker, J. S., Sardeshmukh, P. D., Matsui, N., Allan, R. J., Yin, X., et al. (2011). The twentieth century reanalysis project. *Q. J. R. Meteorol. Soc.* 137, 1–28. doi: 10.1002/qj.776

Cronin, M. F., Gentemann, C. L., Edson, J. B., Ueki, I., Bourassa, M., Brown, S., et al. (2019). Air-sea fluxes with a focus on heat and momentum. *Front. Mar. Sci.* doi: 10.3389/fmars.2019.00430

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., et al. (2011). The ERA-Interim reanalýsis: configuration and performance of the data assimilation system. *Q. J. R. Meteorol. Soc.* 137, 553–597. doi: 10.1002/qj.828

Eastman, R., Warren, S. G., and Hahn, C. J. (2011). Variations in cloud cover and cloud types over the ocean from surface observations, 1954–2008. *J. Clim.* 24, 5914–5934. doi: 10.1175/2011JCLI3972.1

Freeman, E., Woodruff, S. D., Worley, S. J., Lubker, S. J., Kent, E. C., Angel, W. E., et al. (2017). ICOADS Release 3.0: a major update to the historical marine climate record. *Int. J. Climatol.* 37, 2211–2232. doi: 10.1002/joc.4775

Global Climate Observing System [GCOS] (2016). *The Global Observing System for Climate: Implementation Needs. GCOS-200 (GOOS-214)*. Geneva: World Meteorological Organization.

Grigorieva, V. G., Gulev, S. K., and Gavrikov, A. V. (2017). Global historical archive of wind waves based on voluntary observing ship data. *Oceanology* 57, 229–231. doi: 10.1134/S0001437017020060

Hansen, J., Ruedy, R., Sato, M., and Lo, K. (2010). Global surface temperature change. *Rev. Geophys.* 48:RG4004. doi: 10.1029/2010RG000345

Hirahara, S., Ishii, M., and Fukuda, Y. (2014). Centennial-scale sea surface temperature analysis and its uncertainty. *J Clim.* 27, 57–75. doi: 10.1175/JCLI-D-12-00837.1

Huang, B., Thorne, P. W., Banzon, V. F., Boyer, T., Chepurin, G., Lawrimore, J. H., et al. (2017). Extended reconstructed sea surface temperature, version 5 (ERSSTv5): upgrades, validations, and intercomparisons. *J. Clim.* 30, 8179–8205. doi: 10.1175/JCLI-D-16-0836.1

Intergovernmental Panel on Climate Change [IPCC] (2013). Climate change 2013: the physical science basis. in *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, et al. (Cambridge: Cambridge University Press), 1535. doi: 10.1017/CBO9781107415324

JCOMM (2015). *Proceedings of the Fourth JCOMM Workshop on Advances in Marine Climatology (CLIMAR-4) and of the First ICOADS Value-Added Database(IVAD-1) Workshop JCOMM Technical Report No.* 79. Asheville, NC: JCOMM.

JCOMM (2016). *Fourth International Workshop on Advances in the Use of Historical Marine Climate Data (MARCDAT-4) JCOMM Technical Report No.* 131. JCOMM: Southampton UK.

Kennedy, J. J. (2014). A review of uncertainty in in situ measurements and data sets of sea surface temperature. *Rev. Geophys.* 52, 1–32. doi: 10.1002/2013RG000434

Kennedy, J. J., Rayner, N. A., Atkinson, C. P., and Killick, R. E. (2019). An ensemble data set of sea-surface temperature change from 1850: the Met Office Hadley Centre HadSST.4.0.0.0 data set. *J. Geophys. Res. Atmos.* 124. doi: 10.1029/2018JD029867

Kent, E. C., Berry, D. I., Woodruff, S. D., and Taylor, P. K. (2006). Voluntary observing ships: a vital observing system in decline. *Clivar Exchanges* 11, 20–21.

Kent, E. C., Kennedy, J. J., Smith, T. M., Hirahara, S., Huang, B., Kaplan, A., et al. (2017). A call for new approaches to quantifying biases in observations of sea-surface temperature. *BAMS* 98, 1601–1616. doi: 10.1175/BAMS-D-15-00251.1

Kent, E. C., Rayner, N. A., Berry, D. I., Eastman, R., Grigorieva, V., Huang, B., et al. (2019). Observing requirements for long-term climate records at the ocean surface. *Front. Mar. Sci.* doi: 10.3389/fmars.2019.00441

Kent, E. C., Rayner, N. A., Berry, D. I., Saunby, M., Moat, B. I., Kennedy, J. J., et al. (2013). Global analysis of night marine air temperature and its uncertainty since 1880: the HadNMAT2 data set. *J. Geophys. Res.* 118, 1281–1298. doi: 10.1002/jgrd.50152

Kinzel, J., Fennig, K., Schröder, M., Andersson, A., Bumke, K., and Hollmann, R. (2016). Decomposition of random errors inherent to HOAPS-3.2 near-surface humidity estimates using multiple triple collocation analysis. *J. Atmos. Oceanic Technol* 33, 1455–1471. doi: 10.1175/JTECH-D-15-0122.1

Liman, J., Schröder, M., Fennig, K., Andersson, A., and Hollmann, R. (2018). Uncertainty characterization of HOAPS 3.3 latent heat-flux-related parameters. *Atmos. Meas. Tech.* 11, 1793–1815. doi: 10.5194/amt-11-1793-2018

McPhaden, M. J., Busalacchi, A. J., Cheney, R., Donguy, J. R., Gage, K. S., Halpern, D., et al. (1998). The tropical ocean-global atmosphere (TOGA) observing system: a decade of progress. *J. Geophys. Res.* 103, 14169–14240. doi: 10.1029/97JC02906

McPhaden, M. J., Meyers, G., Ando, K., Masumoto, Y., Murty, V. S. N., Ravichandran, M., et al. (2009). RAMA: the research moored array for African–Asian–Australian monsoon analysis and prediction. *Bull. Am. Meteorol. Soc.* 90, 459–480. doi: 10.1175/2008BAMS2608.1

Morice, C. P., Kennedy, J. J., Rayner, N. A., and Jones, P. D. (2012). Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: the HadCRUT4 dataset. *J. Geophys. Res.* 117:D08101. doi: 10.1029/2011JD017187

Pinardi, N., Stander, J., Legler, D., O'Brien, K., Boyer, T., Cuff, T., et al. (2019). The Joint IOC (of UNESCO) and WMO collaborative effort for met-ocean services. *Front. Mar. Sci.* doi: 10.3389/fmars.2019.00410

Poli, P., Hersbach, H., Dee, D. P., Berrisford, P., Simmons, A. J., Vitart, F., et al. (2016). ERA-20C: an atmospheric reanalysis of the Twentieth Century. *J. Clim.* 29, 4083–4097. doi: 10.1175/JCLI-D-15-0556.1

Prytherch, J., Kent, E. C., Fangohr, S., and Berry, D. I. (2015). A comparison of SSM/I-derived global marine surface specific humidity datasets. *Int. J. Climatol.* 35, 2359–2381. doi: 10.1002/joc.4150

Rayner, N. A., Parker, D. E., Horton, E. B., Folland, C. K., Alexander, L. V., Rowell, D. P., et al. (2003). Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res.* 108:4407. doi: 10.1029/2002JD002670

Research Data Archive, et al. (2016). *International Comprehensive Ocean-Atmosphere Data Set (ICOADS) Release 3, Individual Observations. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory*. Boulder, CO: National Center for Atmospheric Research, doi: 10.5065/D6ZS2TR3

Rienecker, M. M., Suarez, M. J., Gelaro, R., Todling, R., Bacmeister, J., Liu, E., et al. (2011). MERRA: NASA's modern-era retrospective analysis for research and applications. *J. Clim.* 24, 3624–3648. doi: 10.1175/JCLI-D-11-00015.1

Saha, S., Moorthi, S., Pan, H., Wu, X., Wang, J., Nadiga, S., et al. (2010). The NCEP climate forecast system reanalysis. *Bull. Am. Meteor. Soc.* 91, 1015–1058. doi: 10.1175/2010BAMS3001.1

Slutz, R. J., Lubker, S. J., Hiscox, J. D., Woodruff, S. D., Jenne, R. L., Joseph, R. H., et al. (1985). *Comprehensive Ocean-Atmosphere Dataset: Release 1. NTIS PB86-105723*. Boulder, CO: NOAA Environmental Research Laboratories, Climate Research Program, 268.

Smith, S. R., Alory, G., Andersson, A., Asher, W., Baker, A., Berry, D. I., et al. (2019). Ship-Based contributions to global ocean, weather, and climate observing systems. *Front. Mar. Sci.* doi: 10.3389/fmars.2019.00434

Smith, S. R., Briggs, K., Bourassa, M. A., Elya, J., and Paver, C. R. (2018). Shipboard automated meteorological and oceanographic system data archive: 2005–2017. *Geosci. Data J.* 5, 73–86. doi: 10.1002/gdj3.59

Smith, S. R., Freeman, E., Lubker, S. J., Woodruff, S. D., Worley, S. J., Angel, W. E., et al. (2016). *The International Maritime Meteorological Archive (IMMA) Format*. Available at: http://icoads.noaa.gov/e-doc/imma/R3.0-imma1.pdf (accessed February 28, 2019).

Smith, S. R., Rolph, J. J., Briggs, K., and Bourassa, M. A. (2009). *Quality-Controlled Underway Oceanographic and Meteorological Data from the Center for Ocean-Atmospheric Predictions Center (COAPS) - Shipboard Automated Meteorological and Oceanographic System (SAMOS)*. Asheville, NC: NOAA National Centers for Environmental Information. Dataset, doi: 10.7289/V5QJ7F8R

Thorne, P. W., Allan, R. J., Ashcroft, L., Brohan, P., Dunn, R. J. H., Menne, M. J., et al. (2018). Toward an integrated set of surface meteorological observations for climate science and applications. *Bull. Am. Meteorol. Soc.* 98, 2689–2702. doi: 10.1175/BAMS-D-16-0165.1

Tokinaga, H., and Xie, S. (2011). Wave- and anemometer-based sea surface wind (WASWind) for climate change analysis. *J. Clim.* 24, 267–285. doi: 10.1175/2010JCLI3789.1

Tsamalis, C., and Saunders, R. (2018). Quality assessment of sea surface temperature from ATSRs of the climate change initiative (Phase 1). *Remote Sens.* 10:497. doi: 10.3390/rs10040497

Vose, R., Arndt, D., Banzon, V., Easterling, D., Gleason, B., Huang, B., et al. (2012). NOAA'S merged land–ocean surface temperature analysis. *Bull. Am. Meteorol. Soc.* 93, 1677–1685.

Willett, K. M., Jones, P. D., Gillett, N. P., and Thorne, P. W. (2008). Recent changes in surface humidity: development of the HadCRUH dataset. *J. Clim.* 21, 5364–5383. doi: 10.1175/2008JCLI2274.1

Woodruff, S. D., Diaz, H. F., Elms, J. D., and Worley, S. J. (1998). COADS Release 2 data and metadata enhancements for improvements of marine surface flux fields. *Phys. Chem. Earth* 23, 517–526. doi: 10.1016/S0079-1946(98)00064-0

Woodruff, S. D., Lubker, S. J., Wolter, K., Worley, S. J., and Elms, J. D. (1993). Comprehensive ocean–atmosphere data set (COADS) Release 1a: 1980–92. *Earth Syst. Monit.* 4, 1–8.

Woodruff, S. D., Slutz, R. J., Jenne, R. L., and Steurer, P. M. (1987). A comprehensive ocean-atmosphere data set. *Bull. Am. Meteorol. Soc.* 68, 1239–1250.

Woodruff, S. D., Worley, S. J., Lubker, S. J., Ji, Z., Freeman, J. E., Berry, D. I., et al. (2011). ICOADS Release 2.5: extensions and enhancements to the surface marine meteorological archive. *Int. J. Climatol.* 31, 951–967. doi: 10.1002/joc.2103

World Meteorological Organization [WMO] (2017a). *WMO No. 471 - Guide on Marine Meteorological Services Global Aspects*, Vol. I. Geneva: WMO.

World Meteorological Organization [WMO] (2017b). *WMO No. 558 - Manual on Marine Meteorological Services Global Aspects*, Vol. I. Geneva: WMO.

World Meteorological Organization [WMO] (2018). *WMO Statement on the State of the Global Climate 2017, WMO No. 1212*. Geneva: WMO.

Worley, S. J., Woodruff, S. D., Reynolds, R. W., Lubker, S. J., and Lott, N. (2005). ICOADS Release 2.1 data and products. *Int. J. Climatol.* 25, 823–842. doi: 10.1002/joc.1166

Xu, F., and Ignatov, A. (2014). *In situ* SST quality monitor (*i*Quam). *J. Atmos. Oceanic Technol.* 31, 164–180. doi: 10.1175/JTECH-D-13-00121.1

Zhang, H.-M., Lawrimore, J. H., Huang, B., Menne, M. J., Yin, X., Sánchez-Lugo, A., et al. (2019). Updated temperature data give a sharper view of climate trends. *Eos* 100. doi: 10.1029/2019EO128229

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REVIEW
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Global Observational Needs and Resources for Marine Biodiversity

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The diversity of life in the sea is critical to the health of ocean ecosystems that support living resources and therefore essential to the economic, nutritional, recreational, and health needs of billions of people. Yet there is evidence that the biodiversity of many marine habitats is being altered in response to a changing climate and human activity. Understanding this change, and forecasting where changes are likely to occur, requires monitoring of organism diversity, distribution, abundance, and health. It requires a minimum of measurements including productivity and ecosystem function, species composition, allelic diversity, and genetic expression. These observations need to be complemented with metrics of environmental change and socio-economic drivers. However, existing global ocean observing infrastructure and programs often do not explicitly consider observations of marine biodiversity and associated processes. Much effort has focused on physical, chemical and some biogeochemical measurements.

Broad partnerships, shared approaches, and best practices are now being organized to implement an integrated observing system that serves information to resource managers and decision-makers, scientists and educators, from local to global scales. This integrated observing system of ocean life is now possible due to recent developments among satellite, airborne, and *in situ* sensors in conjunction with increases in information system capability and capacity, along with an improved understanding of marine processes represented in new physical, biogeochemical, and biological models.

Keywords: biodiversity, ecosystem health, habitat suitability indices, indicators, thresholds, essential ocean variables, essential biodiversity variables, omics

INTRODUCTION

Diversity of life is an essential feature of ecosystems. Depending on the diversity and make up of their biological communities, different habitats may be considered healthy or degraded. Healthy marine ecosystems provide essential services to billions of people, including nutrition, recreation, public safety, and health. Biodiversity—defined here as taxonomic and functional diversity within species, among species, and at the ecosystem level—is, in part, a function of fluctuations in environmental factors. There is evidence that biodiversity in different habitats is changing as a result of climate change and other human pressures (Butchart et al., 2010; Staudinger et al., 2013; Levin and Poe, 2017). Understanding the causes of biodiversity change, and forecasting where, when, and how biodiversity may change, requires building a body of knowledge based on widespread scientific observation and testing of conceptual and quantitative ecological models. Understanding large-scale changes in the distribution of marine species, and understanding whether local changes are part of global, regional, or local processes requires a global science approach. This information is also required to understand biological and physical connectivity among and within coastal and open ocean systems. This approach must be built by networking local and regional observing efforts.

To trace a path to address user needs through better information, the oceanographic community defined a Framework for Ocean Observing in 2012 (Lindstrom et al., 2012). The framework recognized that it is critical to enhance existing ocean observing efforts with routine monitoring of marine biodiversity. This set in motion a process to define sets of Essential Ocean Variables (EOVs) covering ocean physics, biogeochemistry, biology and ecosystems. Yet, baselines to be used as a reference against which to detect changes in marine biodiversity over large scales, and at most coastal, open ocean, or deep ocean locations still need to be defined. The community has to converge on sets of standard methods to collect particular biological EOVs (Miloslavich et al., 2018a) and Essential Biodiversity Variables (EBVs; Pereira et al., 2013; Muller-Karger et al., 2018b). What to observe should be defined by local needs but also must take into account the regional context for assessments that affect multiple industry sectors, localities and countries. Finally, there needs to be an overarching and top-down coordination of regional assessments to enable their integration within a global framework for understanding the condition of and drivers of change for marine biodiversity in to.

Global Partnerships to Understand Marine Life

There have been several notable efforts to develop a global, quantitative understanding of the status of life on Earth. Here we briefly review some of the programs that contribute to a broader understanding of life in the sea, in a systematic manner and over large spatial scales. The good news is that many of the key elements for a global system of coordinated marine biodiversity observations already exist. In their integration lies the key to overall success.

Many countries, individual state agencies, research institutions, and non-governmental institutions hold their own relevant databases. Harmonizing and linking these databases is now a focus of significant effort. To address this pressing need for coordinated biodiversity observations around the globe, the Group on Earth Observations is implementing a Biodiversity Observation Network (GEO BON; Pereira et al., 2013). The Marine Biodiversity Observation Network (MBON), a thematic focus of GEO BON, has emerged as a global community of practice for sustained, operationalized measurements of marine biodiversity. MBON facilitates the coordination between individual monitoring programs and existing networks, promotes monitoring best practices and the contribution of marine biodiversity data, and provides a framework for data management, communication, and application of results. MBON was established because the systematic and coordinated collection of such observations requires leveraging efforts across different institutions, regions, and countries. Standardization of observational approaches, protocols, technologies, and data reporting among biodiversity monitoring programs, as well as open access to observing data, can help overcome some coordination challenges. International cooperation is also required to improve the capacity of nations to satisfy local management requirements while still enabling the reporting to international agreements (e.g., U.N. Convention of Biological Diversity, U.N Sustainable Development Goals, and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), among many).

MBON also serves as the biodiversity arm of GEO Blue Planet, through which the social and economic needs of governments, intergovernmental bodies, and other stakeholders for marine biodiversity data are addressed. This focus on conservation and sustainable use helps to align national and global policy frameworks through responsive monitoring, predictive ecological modeling, and improved ecosystem-based management and decision-making (Österblom et al., 2017). These activities seek to meet emerging needs for marine biodiversity information in national waters and in areas beyond national jurisdiction.

The BioEco Panel of the Global Ocean Observing System (GOOS), also conceived under the Framework for Ocean Observing, was established in 2015 to develop and coordinate efforts in the implementation of a sustained and targeted global ocean observing system. It develops the rationale for EOVs driven by socio-economic and cultural demands of society. The biological EOVs defined by GOOS are complementary to the EBVs, which are being developed under GEO BON (Miloslavich et al., 2018a; Muller-Karger et al., 2019). The goal is to construct regional and global maps of the essential variables on a routine basis, following standard data collection, quality control, and data archiving and distribution protocols. These maps then provide the baselines against which to detect and quantify changes in marine biodiversity.

The Ocean Biogeographic Information System (OBIS) is a standardized, globally-accessible database for the observations of diversity, distribution, and abundance of life in the sea. OBIS was initiated by the Census of Marine Life and adopted by the Intergovernmental Oceanographic Commission (IOC of UNESCO) in 2009 as a project of the International Oceanographic Data and Information Exchange (IODE). It represents the marine community in the development of international data standards for marine biodiversity and ecosystem data. At present, OBIS integrates approximately 60 million occurrences of 120,000 marine species from over 2,600 databases provided by 600 institutions worldwide. OBIS actively supports international processes, such as the UN World Ocean Assessment, the Convention for Biological Diversity (CBD) and its effort to define Ecologically or Biologically Significant marine Areas (EBSAs), and IPBES assessments. In 2017, OBIS expanded beyond species occurrence data to include ecosystem and associated environmental data (De Pooter et al., 2017). OBIS works closely with, and in a similar manner to, the Global Biodiversity Information Facility (GBIF), which also holds many observations of marine species.

The MBON, GOOS, and OBIS have agreed to leverage the strengths and broad partnerships represented by these groups (**Figure 1**). The agreement acknowledges MBON's role to inform and assist development of national and regional observing networks and EBVs, the role of GOOS in articulating the interdisciplinary observing requirements for EOVs, and the role of OBIS to serve local, regional, and international user needs for harmonized biodiversity and biogeographic data. GOOS, OBIS and MBON have agreed to, among other things, to:

1. Advance continuous, long-term, biological ocean observations in a coherent, globally consistent and coordinated way, based on interdisciplinary EOVs and EBVs;
2. Advance development and testing of EOVs, support evolution of EOVs from pilot to mature, and improve global coverage of EOV monitoring and delivery of open-access data products;
3. Foster systematic data quality control, sharing, curation, and aggregation;
4. Support assessments and targets such as those established by IPBES, CBD, the United Nations and others, and liaise with other relevant national and international initiatives;
5. Support linkages within GEO (e.g., to, GEO Wetlands, AmeriGEO) and IOC (e.g., GOOS Regional Alliances, Large Marine Ecosystems, the Deep Ocean Observing Strategy, and OBIS nodes); and
6. Develop global capacity for data collection, data management, and ecological forecasting by sharing and promoting best practices, manuals and guides.

Other efforts that can support the joint work of these three groups serving as data aggregators include the Living Planet Index, the International Union for Conservation of Nature (IUCN), Aquamaps, Reef Life Survey, the Ocean Health Index, BirdLife, FishBase, and global mangrove mapping efforts such as that coordinated by the United States Geological Survey and NASA in the United States, and under the Ramsar Convention, among many other programs. We only highlight a few of these here.

The Living Planet Index (LPI)[1] is an authoritative effort to understand trends in the abundance of biological populations. The LPI employs data from 7,829 populations of 1,234 species of marine birds, mammals, reptiles and fishes and shows a 49% decline between 1970 and 2012. The interpretation is that that the average population size of the species included in the LPI declined by about 50% over that period. Indices should be designed or the LPI augmented to address additional trophic levels, including phytoplankton, macroalgae, and different groups of invertebrates.

The IUCN[2] is a membership-based Union composed of government and civil society organizations that seeks to enable sustainable development. The IUCN has developed a Red List of Threatened Species™, and it is using quantitative criteria to evaluate the extinction risk of over 20,000 marine species through the IUCN Species Program Marine Biodiversity Unit. OBIS contains IUCN conservation status labels for its marine organism records.

AquaMaps[3] is a project that generated predictions of relative habitat suitability as maps at a 0.5° latitude by longitude resolution for over 25,000 marine species, including marine fishes, marine mammals, sea turtles, algae and marine invertebrates (Kaschner et al., 2016). These habitat suitability maps were generated using climatological average oceanographic conditions (temperature, salinity, oxygen concentration, etc.).

[1] http://livingplanetindex.org/home/index
[2] https://www.iucn.org
[3] http://aquamaps.org

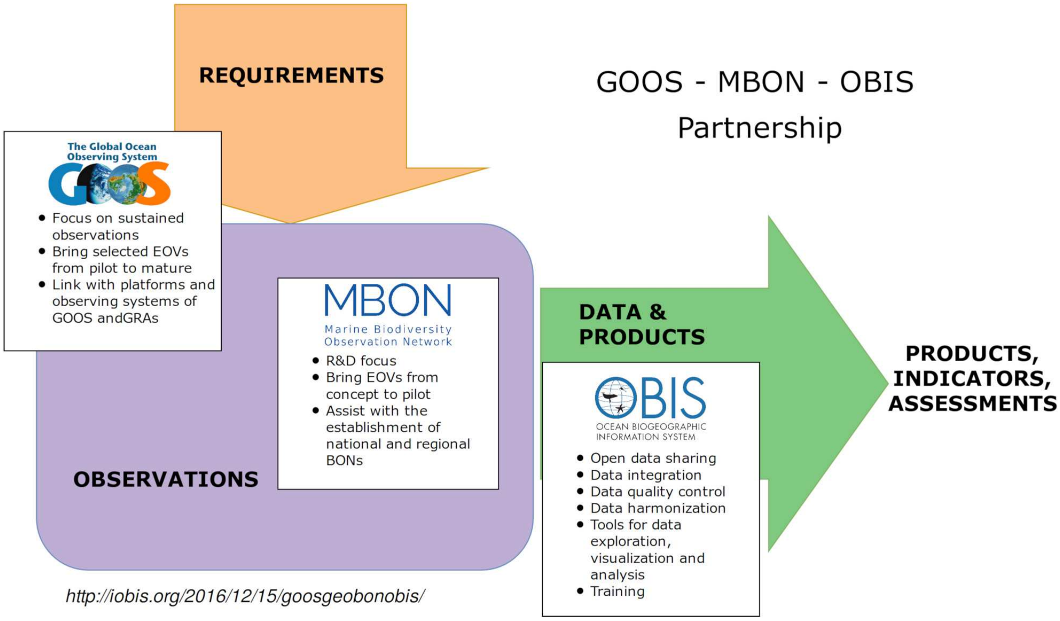

FIGURE 1 | The GOOS-MBON-OBIS collaboration relies on the global framework for ocean observing as a model for a global system integrating marine biology and biodiversity with other types of ocean observations (Benson et al., 2018).

Davies et al. (2017) used the AquaMaps algorithms to conclude that many marine species distributions insufficiently overlap with marine protected areas (MPAs), and, therefore, many species are insufficiently covered by conservation measures as oceanographic conditions shift with climate change. At present, AquaMaps predictions have not been generated at seasonal scales, and this work is needed to understand how different species may overlap in range due to their phenologies or seasonal environmental changes, for example, to address possible interactions with fisheries or other ocean uses.

Reef Life Survey (RLS)[4] is a citizen-science program that trains volunteer SCUBA divers to conduct detailed surveys of fish and coral reef species on shallow rocky and coral reefs, often where human pressures are high (Stuart-Smith et al., 2017, 2018). RLS data are of very high quality, and have been used to evaluate the need for or effectiveness of Marine Protected Areas, possible shifts in species ranges, and to compute the Living Planet Index.

Other efforts include: ReefBase[5], the database of the Global Coral Reef Monitoring Network (GCRMN), as well as the International Coral Reef Action Network (ICRAN). The ReefBase Project is housed at the WorldFish Center in Penang, Malaysia, with funding through ICRAN from the United Nations Foundation (UNF).

FishBase[6] is a global biodiversity information system on finfishes, which covers taxonomy, biology, trophic ecology, and life history of fish, including major commercial fishes. FishBase has information on over 33,000 fish species.

SeaLifeBase[7] has a similar purpose for a broader range of marine organisms. Information aggregated for marine birds may be found in databases such as that maintained by Bird Life International[8].

The above efforts are all dedicated to the understanding and conservation of life in the sea.

REGIONAL AND THEMATIC APPROACHES TO BUILDING AN MBON COMMUNITY OF PRACTICE

Implementation of a global MBON requires organization of regional efforts that engage the scientific and user communities, define biodiversity baselines, and demonstrate applications in conservation and sustainable use of marine resources. If these communities establish regional observing efforts that follow best practices agreed upon and published by MBON and the Ocean Best Practices System (IOC)[9], it will be possible to compare data between localities, within regions and over broader spatial and temporal scales.

The global MBON community met in Montreal, Canada, in May 2018 to discuss the status of the network and future plans, including lessons learned from past and ongoing monitoring efforts of marine biodiversity. The group acknowledged that while long-term regional and international scientific programs are needed to assess biodiversity and track the impacts of

[4] https://reeflifesurvey.com
[5] http://www.reefbase.org/about.aspx
[6] http://fishbase.org
[7] http://sealifebase.org
[8] http://www.birdlife.org/
[9] http://www.oceanbestpractices.org/

environmental change on scales large enough to capture the processes and mechanisms operating in the ocean, the enormous spatial extent of the ocean still presents a significant challenge. Traditional survey methods can be very expensive and thus there is a need to better integrate various methods of remote sensing of biodiversity (Muller-Karger et al., 2018a). Remote areas, and areas with extreme weather such as the Arctic and high southern latitudes present additional challenges. Because human and financial resources are limited, a major goal of MBON and related groups must be facilitation of technology access and development of human capacity. Strengthening existing networks and programs remains the priority before creating new, parallel, and potentially competing structures and organizations. The latter scenario of redundant structures and organizations inevitably incurs human, financial, and other costs, inhibiting everyone's ability to mainstream biodiversity themes in ocean observing.

Changes in marine biodiversity are being documented from the Arctic to Antarctica. Many nations and regions need information on how these changes affect ecosystem services. MBON activities are increasingly organized as large, multi-sector, interdisciplinary regional efforts. One of these MBON efforts seeks to organize observation of marine ecosystems in the Americas from pole to pole (see below). MBON has also been recognized as a core contribution to the emerging All-Atlantic Ocean Observing System (AtlantOS). Most recent to emerge is the Asia Pacific MBON, announced at the GEOSS Asia-Pacific Symposium in October 2018. MBON is also participating in GEO Blue Planet efforts to support marine biodiversity and fisheries monitoring activities in developing nations, including Small Island Developing States. Some of these regional programs are described below.

US MBON

In 2014, the United States initiated a prototype national network to monitor marine biodiversity with support from NASA, the Department of the Interior's Bureau of Ocean Energy Management (BOEM), and several NOAA offices including the National Marine Sanctuaries, Oceanic and Atmospheric Research labs and Office of Ocean Exploration, National Marine Fisheries Service, National Ocean Service, and the National Environmental Satellite, Data, and Information Service (NESDIS). The United States National Science Foundation has participated in important aspects of this effort and initial efforts were supported with a significant oil industry investment. Demonstration efforts were launched in multiple locations: the Florida Keys; Gulf of Mexico (Flower Garden Banks); California's Monterey Bay and Santa Barbara Channel; and the Chukchi Sea in Alaska, with new sites to be announced in late 2019. These networks integrate new and long-term observations from satellite, laboratory, *in situ* observing systems, and other ocean research and monitoring activities to provide a broader picture of how marine ecosystems are changing and identify drivers of these changes.

The US Integrated Ocean Observing System (US IOOS), the US contribution to the network of GOOS Regional Alliances, provides overall coordination for the US MBON effort. IOOS Regional Associations are helping to facilitate knowledge transfer, tools, and sharing of best practices and data. US MBON participation in global MBON efforts has fostered US IOOS coordination of biodiversity monitoring and data management approaches with Canada through cooperation with Fisheries and Ocean Canada (DFO), and demonstrated how certain biological observing methods and approaches can be implemented in the context of a GOOS Regional Alliance. The MBON efforts led to convergence within US IOOS on the use of the Darwin Core standard schema for biological observations.

The US MBON and IOOS partners have made significant contributions to the development of new and innovative means to assess marine biodiversity. US MBON projects have been central in developing best practices for eDNA and demonstrating its utility for biological observing, and they have advanced the means to collect eDNA samples using autonomous underwater vehicles. US MBON partners are also developing image analysis techniques targeted at underwater image classification for use in an operational setting. Remotely sensed seascape maps (a US MBON product now being distributed for the global ocean through a partnership with the NOAA National Environmental Satellite, Data, and Information Service or NESDIS), as well as models, are being used to scale *in situ* observations, and to identify and classify habitat for targeted sampling and management activities.

MBON Pole to Pole Efforts in the Americas

The MBON Pole to Pole initiative was intended as a major decadal-scale activity spanning the Arctic, the Americas, and Antarctica that would establish the infrastructure and partnerships needed for global expansion of the network. MBON Pole to Pole focuses on capacity building and applied science for conservation and management of marine living resources with an emphasis on: 1) use of common methods, 2) repeated sampling at the same sites, 3) establishment of similar seasonal and temporal sampling resolution, 4) use of the Darwin Core data schema, and 5) open data sharing via OBIS.

The MBON Pole to Pole is a voluntary network of cooperating research institutions, marine laboratories, parks, and reserves engaged in monitoring and research to document marine biodiversity status and change. Initial efforts are focused in the Americas region along the Pacific and Atlantic coasts (Cruz et al., 2003; Escribano et al., 2003; Miloslavich et al., 2011; **Figure 2**).

Marine Biodiversity Observation Network Pole to Pole activities in the Americas region are being coordinated with initiatives such as the Caribbean Marine Atlas (CMA-2 Project) and the Southeast Pacific Data and Information Network in Support of Integrated Coastal Area Management (SPINCAM) program, both under the umbrella of the IOC-IODE and similar efforts. MBON incorporates historical time series data such as those collected by the CARIACO Ocean Time-Series (Muller-Karger et al., 2019) and the Caribbean Coastal Marine Productivity (CARICOMP) effort (Cortés et al., 2019). Such datasets allow interpretation of regional changes in terms of oceanographic regimes,

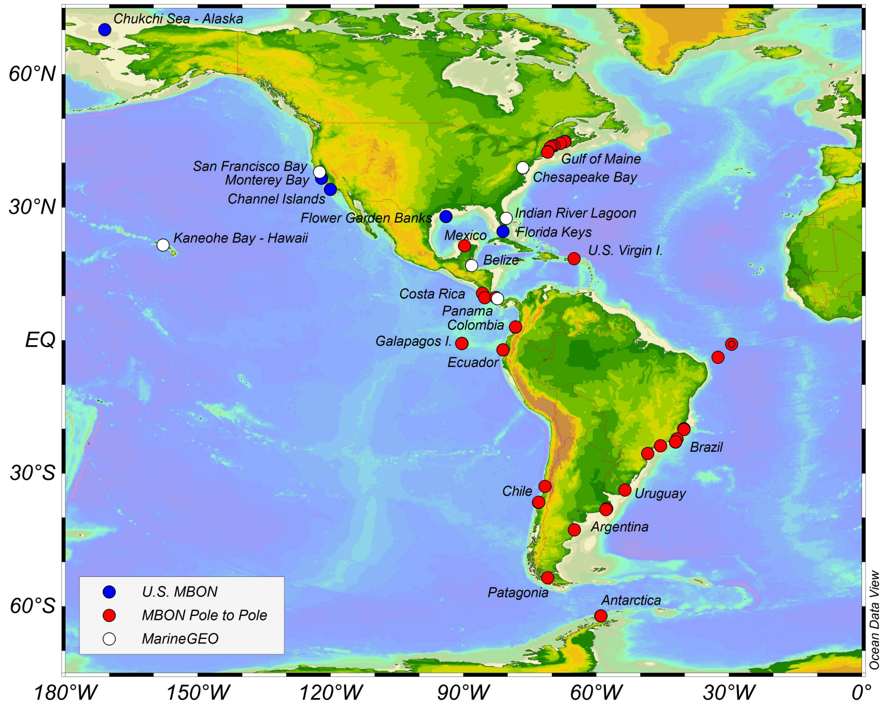

FIGURE 2 | Map of US MBON, MarineGEO, and MBON Pole to Pole in the Americas sites at the time of publication.

e.g., the El Niño Southern Oscillation (Chavez et al., 2003). Field data collection efforts include biodiversity and environmental properties (e.g., *in situ* temperature) using protocols developed by the South American Research Group on Coastal Ecosystems (SARCE), which was established in 2010 to investigate marine diversity and biomass in rocky intertidal ecosystems along both coasts of South America (Miloslavich et al., 2016).

Marine Biodiversity Observation Network Pole to Pole leverages several GOOS Regional Alliances (IOCARIBE for the wider Caribbean region and Gulf of Mexico; the GOOS Regional Alliance for the South-East Pacific, GRASP; the Regional Alliance for the Upper Southwest and Tropical Atlantic. OCEATLAN; and US IOOS) as well as AtlantOS.

Circumpolar Biodiversity Monitoring Program

The Circumpolar Biodiversity Monitoring Program (CBMP) includes several countries working toward harmonized and integrated monitoring across borders and regions. CBMP is an effort of the Arctic Council's Conservation of Arctic Flora and Fauna (CAFF)[10], it represents an agreement across Arctic States to compile, harmonize and compare results from existing Arctic marine biodiversity and ecosystem monitoring efforts, across nations and oceans, coordinated through a network of scientists and traditional knowledge holders, governments, Indigenous organizations and conservation groups. Six Expert Networks (Sea ice, biota, Plankton, Benthos, Marine fishes, Seabirds and Marine mammals) have identified key elements, called Focal Ecosystem Components (FECs), of the Arctic marine ecosystem. Changes in FEC status likely indicate changes in the overall marine environment. For the purposes of reporting and comparison, eight physically and biogeochemically distinct Arctic Marine Areas (AMAs) were identified.

One output from the CBMP (**Figure 3**) identifies the current gaps in monitoring across the Arctic (an area of over 30 million Km^2). Each concentric ring represents a group of focal ecosystem components and each segment represents a specific Arctic Marine Area. The graphic conveys the current status of monitoring across these Arctic Marine Areas, indicating for example where monitoring coverage is sporadic or where it is sufficient. The graphic shows the status of marine biodiversity monitoring by Focal Ecosystem Component and Arctic Marine Area to help visualize gaps where information is lacking, and where monitoring efforts should be focused. The graphic is then broken down into separate wheels for each of the expert networks within the marine CBMP to identify for each FEC status and trends for which data exists[11]. This type of output from a regional monitoring program is proving useful in communicating with and convincing decision makers about the importance of funding sustained monitoring.

[10]https://www.caff.is/monitoring

[11]https://arcticbiodiversity.is/index.php/monitoring-status-and-advice

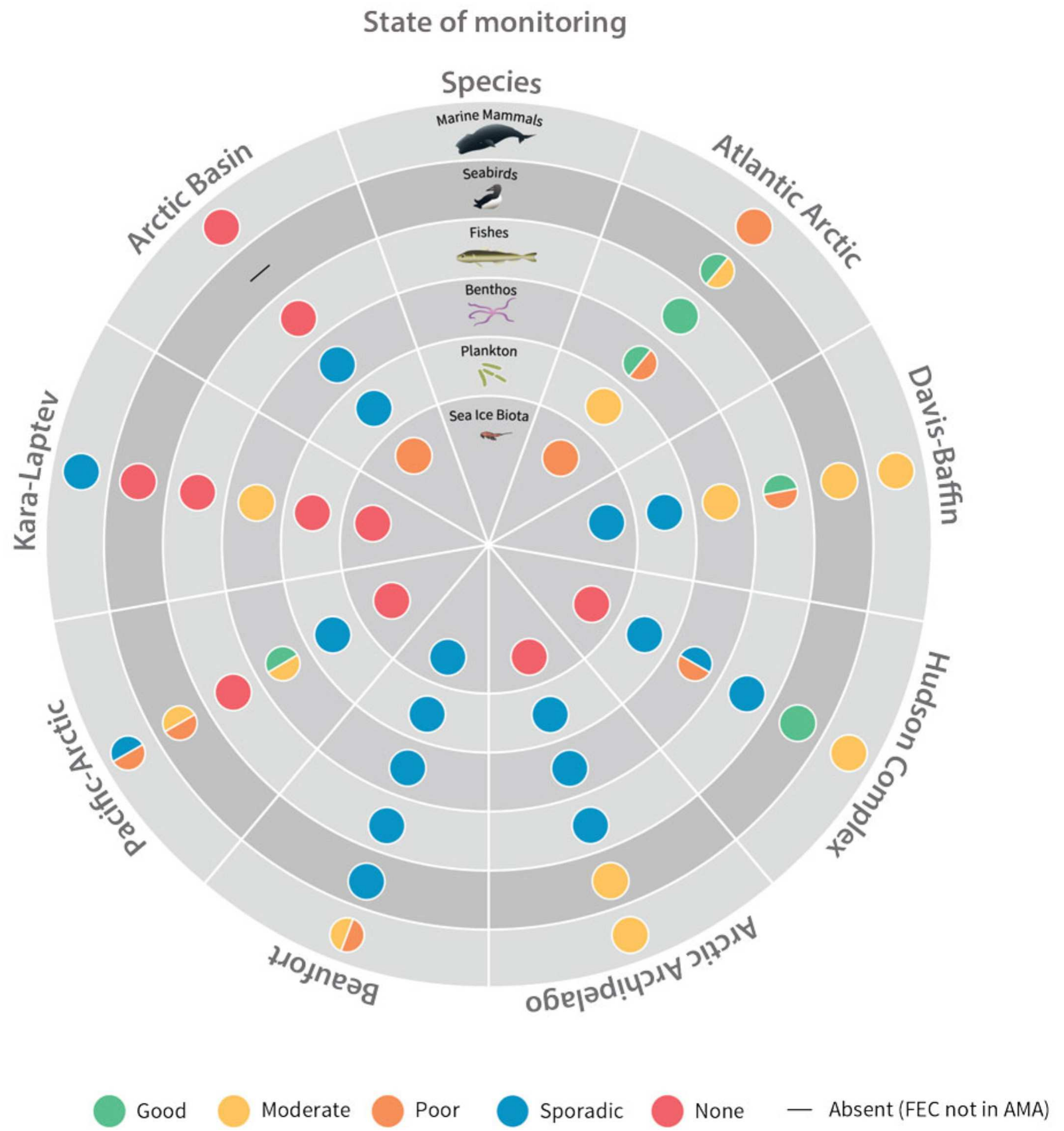

FIGURE 3 | Current status of monitoring across Arctic Marine Areas. Each concentric ring represents a group of focal ecosystem components and each segment represents a specific Arctic Marine Area.

Global Ocean Acidification Observing Network

The Global Ocean Acidification Observing Network (GOA-ON)[12] represents a thematic network for which collection of and access to biological observations are increasingly important. GOA-ON is a global, long-term observing network dedicated to monitor ocean acidification (OA), understand its biological effects, and support forecasts allowing for adaptation to OA. GOA-ON and MBON seek to collaborate to enable the collection of observations to support understanding of biological impacts from OA and the effects of biological processes on OA. This multidisciplinary approach is needed to understand how OA affects ecosystems and marine living resources.

The network of OA observations at coastal sites, and from ships or buoys in deeper water, is expanding, but collection of concurrent biological observations at those sites is more limited. Furthermore, research on OA-driven biological impacts has largely been limited to laboratory and confined sites. Without simultaneous collection of biological observations, it is difficult to know how OA affects marine biota *in situ*, especially marine calcifiers with already demonstrated *in situ* negative effects. Identification and development of suitable indicators, combined with the integration of sustained observations from GOA-ON and MBON, would allow for long time series observations at specific locations where measurements of

[12]www.goa-on.org

biological community composition and activity are collected in tandem with hydrographic and biogeochemical variables.

Global Ocean Acidification Observing Network is actively involved in supporting SDG 14.3 (UNESCO, 2018). The GOA-ON data portal serves[13] metadata for a variety of assets, and some limited data products and visualizations of data streams. While primarily chemical and physical variables at present, there is desire to have interoperability with biological data portals; this presents an opportunity for the MBON and GOA-ON communities to develop shared approaches through collaboration.

OBSERVATIONS AND DATA PRODUCTS TO MEET USER NEEDS

MBON, GEO Blue Planet, and others recognize several broad categories of users of marine biodiversity data: managers, natural and social scientists, private organizations, and governmental and non-governmental organizations. Specific sectors include commercial and recreational fisheries; cruise, hotel and other aspects of tourism; extractive industries such as oil, gas, other energy development and mining; and maritime transportation. Thus, they include managers and planners addressing conservation and multiple and often competing uses of marine resources. Researchers, educators and the general public use these data for activities ranging from scientific inquiry, and the development of pharmaceuticals to recreation. Each user operates at unique spatial and temporal scales and for particular purposes.

The context of planning and management of ocean uses is of particular interest. For example, applications may use information about seasonal biodiversity hotspots, or species aggregation areas, to minimize negative interactions with an industry such as mineral and oil extraction, maritime transport, or fisheries. Specific applications may help to minimize possible bycatch by specific fisheries sectors, route ship traffic to avoid areas of marine mammal migrations, or manage noise that may harm specific marine fauna. The information is intended to define thresholds of vulnerabilities in different habitats. Such applications support marine spatial planning that is temporally dynamic.

Open access to information, analyses and syntheses is critical to an integrated global observing system that serves the broad set of users outlined above. Benson et al. (2018) promote broad acceptance of the Findable, Accessible, Interoperable, Reusable (FAIR) principles for data (Wilkinson et al., 2016). While FAIR does not necessarily imply access at no cost, for MBON, open access means that any user can download the data they require without prerequisites or limitations, and can re-use the data as long as they cite the original datasets. A centralized open access data system exposed through easy and user-friendly portals, tailored to the needs of different stakeholders, is essential. Putting this in context, investment in new or sustained observations of biology should be guided by iterative interactions with users that enable identification of data targets and establish priorities for the observing system.

Implementing such critical applications is difficult today because current databases and our knowledge on biodiversity is uneven in many parts of the world. Historically, sampling efforts have been highly variable (Chaudhary et al., 2017). There have been and continue to be mismatches in long-term observational plans, inequalities in technical and research capacity, and lack of funding and trained scientists in many regions (Hui et al., 2011). Significant spatial and temporal observational gaps remain over large geographic areas around the planet (Muller-Karger et al., 2018b). For example, biological records stored in OBIS show that the density of records of observations in tropical areas and the southern hemisphere is significantly lower than in the northern hemisphere. A major goal of MBON is to encourage contributions by the global ecological community to OBIS to address this. In areas where density of observations is high, challenges include prioritization of core monitoring requirements, integration across existing monitoring activities, and investment in standardized observations and technologies to fill gaps. Maintaining observations for long enough to detect shifts and trends in marine life represents a particular challenge. There is also a challenge with encouraging the science and management communities to report observations to databases like OBIS in a timely fashion.

Compilation of historical data of biological *in situ* responses to environmental change and variability through data archaeology can provide long-term data and can enhance data synthesis toward measuring changes against baselines to identify the most vulnerable habitats and ecosystems. Data management activities and platforms are needed that can support integration of biological observational data with physical and biogeochemical parameters to understand interactions of species, changes to habitats, and impacts of environmental variations from multiple sources and stressors. A common infrastructure with a shared, open access data platform is critical to pull this all together.

Ocean observing communities must develop and endorse operational best practices for observatory design, sample collection and calibration, data management, and product dissemination of multi-level data products. To enable this process, the IOC hosts the Ocean Best Practices System[14]. Best practices are documented procedures that, through experience and research, consistently have yielded results superior to those achieved by other means and can be used as a benchmark, and ideally will become widely adopted (Pearlman et al., 2018). Coordination is important to accelerate uptake of new technologies, many of which aim to reduce the time between data collection and quality-controlled data availability through automation. This improves temporal and spatial resolution while reducing long-term costs.

[13] http://portal.goa-on.org/

[14] http://www.oceanbestpractices.org/

GAPS AND CHALLENGES

Better integration of biological observing into the global observing system has challenges that can be overcome working as a community. There is a need for better understanding of critical user needs in different localities and to establish an iterative process that allows review of products at every phase. Integration and widespread implementation of biodiversity observations will require an accelerated development, and lower costs, of new technologies such as those outlined by Boss et al. (2018) and Lombard et al. (2019) (this Frontiers issue in the context of Ocean Obs 19). Inherent challenges of distributed, inter-disciplinary networks include ensuring reproducibility of data products and processes, as well as the technologies involved, promoting data literacy that bridges oceanographers and biologists with data science experts, continued incentives for sharing data (Hazen and Bromberg, 2018), while also realizing that just sharing data and code are not enough—workflows must also be shared (Wright, 2016; Benson et al., 2018).

Development of indicators to address global policy requirements or local management questions is also an area that requires agreement to identify and prioritize observing and data targets. This is a fundamental objective of the development of EOVs and EBVs, as these are the information products from which indicators are assembled. Agreement on methods and common standard sampling protocols still presents many opportunities as well as a solution to ease challenges of interoperability of approaches and data and to facilitate capacity building for expanded sampling coverage. As noted previously, in some areas density of observations is high - but in other areas where the physical environment is difficult to sample or where resources do not exist to support observing efforts, there are significant observation gaps. The global community can better work together to fill these gaps by pursuing facilities, funding and human resources for monitoring; ensuring standardized approaches to collection of biological and biodiversity observations; and providing opportunities for young researchers such as internships, scholarships, and exchanges toward educating new practitioners in shared approaches. Educational organizations such as UNESCO and its field-specific projects such as Ocean Teacher Global Academy (OTGA), the Partnership for Observation of the Global Ocean (POGO), and many academic, private, and informal groups provide platforms for knowledge sharing (Miloslavich et al., 2018b).

Training and educational activities help address these challenges and enhance our understanding of regional and global biodiversity and biogeography patterns.

NEW METHODS AND INTEGRATIVE APPROACHES

The range of methods for studying and assessing biodiversity is large, yet it exists within largely self-contained expert communities. The potential to deploy many of these methods globally is variable and limited. This challenges our ability to conduct biodiversity assessments within national Exclusive Economic Zones (EEZs) and between the EEZs or in specific areas of interest in different countries and regions with relevance to the CDB or UN SDGs. In the sections below, we describe candidate biodiversity monitoring methods that show promise for the global observing community.

Ultimately, observations lead to the ability to interpret change in the context of environmental data (e.g., Austin, 2007; Helmuth, 2009; Mislan and Wethey, 2011; Woodin et al., 2013). The relative advantages and disadvantages of correlation ("climate envelope") versus process-based modeling of species distributions and biodiversity patterns remains an active area of discussion and debate (Pacifici et al., 2015), but both are important tools to enable ecological forecasting and species distribution modeling (Rougier et al., 2015).

Remote Sensing

The assessment of changes in marine life to sustain ecosystem services, including food provisioning and water security around the world, requires innovation in the combination and application of *in situ* and remote sensing observations (Geller et al., 2017). Field surveys cover only small areas but are necessary to evaluate the elements and processes defining marine biodiversity, especially at depth. Remote sensing using satellites offers the only feasible means to assess patterns in surface-ocean EOVs at regional or global scales repeatedly and over long periods (Miloslavich et al., 2018a,b; Muller-Karger et al., 2018a). Combining synoptic environmental data of ocean color, sea surface temperature, sea surface salinity, sea surface height, and sea surface winds provides a means to characterize past and current variability in biogeographic regions (i.e., 'Seascapes') across the globe (Kavanaugh et al., 2018). Ultimately, this information is fundamental for any capability to predict changes in ocean ecosystems using models.

The assessment of coastal and marine biodiversity using remote sensing is largely based on the correlation of traits of organisms and of species' natural 'tolerance windows' with the habitats in which they live, and then tracking with remote sensing how these habitats change over time. Much effort is currently placed on determining these patterns from information contained in the sunlight scattered and absorbed, or light emitted (as in fluorescence), by different species, species populations and communities, and habitats. These light-based signals contain information on functional phytoplankton groups, colored dissolved matter, and particulate matter near the surface ocean, and of biologically structured habitats (such as floating and emergent vegetation and also benthic habitats like coral, seagrass, algae). EOVs from remote sensing can be used to derive sets of EBVs (Pereira et al., 2013), including the distribution, abundance, and traits of groups of species populations, and to evaluate fragmentation of habitats.

Satellite ocean color observations of the surface open ocean were first demonstrated with the Coastal Zone Color Scanner (CZCS; 1978–1986). Since then, a number of ocean color missions have been flown by different countries over the years. These data typically have a spatial resolution of between about 300 m and 1 km pixels, with the intent of providing near-daily coverage of the global ocean. A new generation of ocean color sensors is being planned to continue time series that provide important regional and global ocean coverage in order to understand long-term changes in phytoplankton biomass and to make inferences about changes in carbon pools and fluxes in the global ocean. The new sensors will measure additional colors that will improve our ability to monitor biodiversity in pelagic ocean waters and quantify phytoplankton functional types, such as nitrogen-fixing organisms (e.g., Trichodesmium), calcifiers (coccolithophores), producers of dimethyl sulfide or DMS (e.g., Phaeocystis), silicifiers (e.g., diatoms), and identify various harmful algal and bacteria blooms. For example, NASA is building the hyperspectral Plankton, Aerosol, Cloud, and ocean Ecosystem (PACE) imaging spectrometer mission, for launch in the 2022–2023 timeframe. This will complement the European Space Agency's Sentinel-3A and Sentinel-3B satellites with the two multispectral Ocean and Land Color Instruments (OLCI). Together, these OLCI sensors provide near daily global ocean coverage.

Space agencies of the world are also evaluating plans to design satellite missions to observe coastal areas. These habitats change rapidly with fluctuations in tides, temperature, salinity, wind and river input, pollution, and physical destruction. These changes occur over scales directly relevant to human activity, in the order of meters to tens of meters. Making these observations requires a new generation of satellite sensors able to sample with unique characteristics of high spatial resolution (∼60 m pixels or smaller), high spectral resolution (∼5 to 10 nm in the visible and 10 nm in the short-wave infrared spectrum for atmospheric correction, and aquatic and vegetation assessments), high radiometric quality and high signal to noise ratios, and high temporal resolution (hours to days). This approach is called "H4" imaging (Muller-Karger et al., 2018a). Global H4 coverage of coastal habitats can be achieved with several concurrent H4 satellites. These complement missions such as Landsat and the Sentinel 2 series, and planned hyperspectral missions such as the NASA Surface Biology and Geology (SBG) mission. The SBG concept is in accelerated development and will provide hyperspectral visible and short-wave infrared observations at 30-m spatial resolution, with multiple bands in the infrared at slightly coarser spatial resolution. The objective is to provide observations relevant to biodiversity of continental areas, including inland fresh water bodies and global coastal waters (The name SBG may change as the mission concept evolves).

In situ Observation Methods

Boss et al. (2018) and Lombard et al. (2019) (*this issue*) describe sensors, instruments, platforms, and methods that are available at present for *in situ*, operational observations of plankton. The goal of plankton observations is to understand the basis of the food chain, which responds to changes in the environment due to natural abiotic and biotic forcing (bottom-up forcing) and direct human pressures such as fisheries, other extractive practices, and pollution (top-down forcing) (see Muller-Karger et al., 2014). There is a need to go "beyond fluorescence" and collect biological observations that allow the characterization of how carbon, micro-nutrients, and energy are partitioned across diverse forms of life (Boss et al., 2018). This information is important also to understand where and when food webs may develop and sustain ecosystem services, such as fisheries of one type of another, carbon storage or release, or sediment formation.

Measurements of optical characteristics of the water, including absorption, scattering, attenuation and fluorescence, are now routine in oceanography. They characterize bulk properties of small particles and organisms (microns to millimeter-size objects). They can be deployed on CTD (conductivity-temperature-depth) rosettes and in-line flow-through systems on boats, but increasingly also on moorings and other autonomous devices like Argo floats and gliders.

Some devices measure particle size and concentration, such as Coulter Counters and the LISST series of instruments. Other devices image organisms and classify them to some level of taxonomy. An advanced optical device that provides measurements to quantify the biodiversity of phytoplankton is the Imaging Flow Cytobot (Brownlee et al., 2016; Hunter-Cevera et al., 2016). The Imaging Flow Cytobot may be deployed as part of an in-line flow-through system on ships, which provides a means to survey plankton over long distances. It may also be deployed as part of a moored buoy system to measure how phytoplankton is changing over time, including the phenology of individual or aggregate phytoplankton communities, and provide measurements of which organism may dominate during a bloom. Other flow cytometers used in oceanography include the CytoSense/Cytobuoy. Zooplankton imaging is now also possible with a number of devices, such as the ZooScan, ISIIS (*In situ* Ichthyoplankton Imaging System; Cowen and Guigand, 2008), and the Underwater Vision Profiler (Picheral et al., 2010).

These devices, especially the flow cytometers and imaging devices, are still very expensive; there is a need to develop inexpensive versions of such technologies for more widespread use. Imaging devices also generate large quantities of data and images that require automated expert classification, so a number of information technology challenges (machine learning, data curation, archival, distribution) must also be addressed.

Acoustic monitoring can complement other types of sensor-based or visual observations of biodiversity. This can include active acoustics, such as echosounders that pulse and record reflected sound to support biomass and abundance estimates, spatial and temporal distributions, and measurement of size distributions and population structure; transducers in fixed locations that record sound to identify and count fish; or acoustic cameras that create high resolution, three-dimensional digital images of the water column (Discovery of Sound in the Sea, dosits.org). Passive acoustic monitoring uses technology such as hydrophones to listen to ocean ambient sound, augmenting other survey methods and documenting the acoustic environment to support research on the impacts of ocean noise to marine life. Increase in ocean noise raises concerns about the acoustic quality of marine habitats and could have consequences for many species and ecosystems.

Animal telemetry approaches – including use of archival, satellite, and acoustic tags and receivers – allow understanding of environmental conditions as well as the movements and behavior of some marine life, including cetaceans, pinnipeds, turtles, sharks, rays, and fishes. In the 2018 Future Science

Brief of the European Marine Science Board, Benedetti-Cecchi et al. (2018) reviewed the literature describing availability of information about marine animals collected with biologging technology. Animal tagging is important for research on the behavior and condition of animals as well as for collection of oceanographic data about the habitats they occupy, transit and use. Integration of animal tagging information for higher trophic level species with data collected from other parts of the system can help answer questions about impacts on top predators and protected species. Advances in transmitters, receivers, and data storage tags over the past decades enable collection of high-quality biological and oceanographic observations on timescales varying from days to years as the animals move through aquatic habitats (US Animal Telemetry Network Implementation Plan)[15]. The resulting data can inform management of fisheries and protected species, assessments of impact of human activities on aquatic species, and improved ocean models and forecasts.

Other novel methods of *in situ* sampling have focused on recording environmental conditions for comparison against physiological tolerance data (Singer et al., 2016). Such measurements have shown surprisingly high spatial and temporal variability in factors such as pH and temperature (Hofmann et al., 2011) which can potentially impact our predictions of environmental change on biodiversity and species distribution patterns (Kroeker et al., 2016). For example, temperatures recorded *in situ* on coral reefs indicate patterns and extremes that are sometimes, but not always, directly extrapolated from measurements of SST (Smale and Wernberg, 2009; Castillo and Lima, 2010). Environments such as intertidal systems and shallow coral reef habitats (Leichter et al., 2006) are especially problematic in this regard. In intertidal systems, biomimetic instruments such as the 'Robo-Limpets' deployed as part of MBON Pole to Pole have demonstrated that geographic patterns based on these instruments, which record conditions directly relatable to those experienced by the organism, can yield radically different predictions from those based on large-scale pixels such as from remote sensing (Helmuth et al., 2002). These observations point to the strength of combined approaches that capitalize on the importance of large-scale, continuous data available from remote sensing with more targeted approaches based on *in situ* monitoring (Geller et al., 2017; Bates et al., 2018).

Multi-Omic Sampling

Frameworks of biodiversity assessment set forth in agreements such as the CBD urge that observational activities include every level of biological organization. This is echoed by the biological and ecological EOVs under development within GOOS, such as variables for mangroves and corals, as well as microbes. Thus, the components of biodiversity observation networks, such as MBON, must be able to provide integrated insight on molecular, cellular, physiological, population- and community-level diversity, as well as ecosystem-level integrity (Bednaršek et al., 2017; Goodwin et al., 2019). At the finer scale of this continuum, novel, increasingly cost-effective approaches to assess diversity, variation, and anthropogenic impact at the molecular and cellular level are of high interest due to their sensitivity, ability to augment existing methods of observing macro-organisms (e.g., Bourne et al., 2016; Apprill, 2017; Bierlich et al., 2017; Stat et al., 2018), and their ability to report on the microbial life which is central to the functioning of the changing oceans (e.g., Moran, 2015; Sunagawa et al., 2015; Stat et al., 2017; Buttigieg et al., 2018). We thus propose that "omics" approaches – those that analyze organisms at the molecular level, including DNA, RNA, proteins, and small molecules – are utilized to ensure that an integrated and global MBON can report on biodiversity across scales. Omics encompasses fields such as genomics, transcriptomics, proteomics, and metabolomics as well as their application to environmental samples (e.g., metagenomics, metatranscriptomics, metabarcoding; see Aguiar-Pulido et al., 2016 for an overview). Omics approaches identify organisms, their status, and their adaptation potential and are predictive, showing how these might change in response to environmental change).

Over the last decade, omics theory, methods, and applications have been transferred from the research domain into operational and long-term observation settings, and progress has already been linked to MBON's core objectives through demonstration projects analyzing microbial, invertebrate, and vertebrate target species and populations (Andruszkiewicz et al., 2017; Djurhuus et al., 2017, 2018; Goodwin et al., 2017). In the marine realm, omics methodologies and standards have been driven forward by large-scale surveys of ocean waters such as the Global Ocean Sampling (GOS) expedition (Rusch et al., 2007), the TARA Oceans expedition (Karsenti et al., 2011; Sunagawa et al., 2015), the California Cooperative Oceanic Fisheries Investigations (CalCOFI; Goodwin et al., 2019), and Ocean Sampling Day (OSD; Kopf et al., 2015) with support from organizations such as the Genomic Standards Consortium[16] (Field et al., 2011). They have been contextualized by multi-biome initiatives primarily represented by the Earth Microbiome Project (EMP; Thompson et al., 2017). In parallel, omics-enabled marine observatories and time series have emerged from the poles[17] (e.g., Soltwedel et al., 2013) to temperate (Andruszkiewicz et al., 2017) and tropical/subtropical latitudes (Steinberg et al., 2001; Karl and Church, 2014; Muller-Karger et al., 2019). Indeed, as an indicator of future integration, some of these efforts have interfaced with established ocean observing activities such as GEOTRACES[18] (Biller et al., 2018).

Currently, the bulk of omics ocean observation is directed toward marine microbes. Thus, it addresses a major gap in our observational capacities: most contemporary ocean observation programs do not target microbes, despite their key role in driving major biogeochemical cycles and essential ecosystem services (Boetius et al., 2015; Moran, 2015). Omics technologies–with their falling cost and growing practicality–are our best available

[15]https://ioos.noaa.gov/project/atn/

[16]http://gensc.org/

[17]http://mars.biodiversity.aq

[18]http://www.geotraces.org/

option in meeting growing calls for understanding the global microbiome (e.g., Dubilier et al., 2015) and supporting the emergence of the Microbial EOV under development within the GOOS Biology and Ecology Panel (Miloslavich et al., 2018a; Muller-Karger et al., 2018a).

Be it for microbes or metazoans, omics is providing new insights and sensitive tools to detect shifts in community assemblages in response to changes in environmental conditions that can support management of marine environments in the face of rapid global change (e.g., Cordier et al., 2017; Goodwin et al., 2017; Pawlowski et al., 2018). However, the impact of omics observation is strongly dampened by the lack of global, standardized, and well-contextualized datasets and accompanying best practices (Buttigieg et al., 2018). There is a need to engage international networks of omics observers and collectively interface with established global observation programs.

Part of this need is being addressed by existing efforts such as the Genomic Observatories Network (Davies et al., 2014) and the emerging Global Omics Observatory Network (GLOMICON)[19], an outcome of the AtlantOS project[20]. Such networks are facilitating the alignment of protocols and information standards, as well as activities such as round-robin calibrations to enable omics to move closer toward operational biodiversity monitoring systems, e.g., omics applications that complement biodiversity surveying of marine macrophytes (Zardi et al., 2015; Neiva et al., 2017; Hamaguchi et al., 2018). These networks also offer avenues for methodological comparisons (e.g., Pesant et al., 2017; Fahner et al., 2018), (meta)data management solutions (e.g., Deck et al., 2017), and emerging reporting practices (e.g., Nilsson et al., 2018) to attract more rapid reaction from the ocean omics community.

MBON offers a vital rallying point to fully realize the immense potential of multi-omic observation; its focus on operationalizing biodiversity observation will be essential to channeling and guiding marine omics through the next decade. Thus, we argue that:

1. The accessibility and long-term value of omics data should be more widely communicated within the ocean sciences.
2. Marine omics initiatives, particularly long-term or observatory-grade projects, should join and help shape omics observatory networks to present a coordinated front when interfacing with established ocean observation networks.
3. Networks of marine omics observers and MBON should align and guide one another to efficiently enhance and/or complement broader biodiversity observational capacities with molecular methods, with an initial focus on metagenomics and marker gene sequencing.
4. Omics-based observations should be rigorously tested before being integrated into routine ocean observations programs, preferably through a coordinated and international set of facilities.
5. Global baselines of standardized omics observations must be gathered, particularly in undersampled regions of the World Ocean to develop a basis from which changes may be detected with greater consistency.
6. Omics data must be exchangeable in a FAIR-compliant (Findable, Accessible, Interoperable, Reusable) manner, and omically enabled observatories must be able to 1) seamlessly understand and query one another's data and 2) automatically synchronize and/or submit their data with aggregators such as GBIF and OBIS.
7. The GOOS Biological and Ecological EOVs, particularly the Microbial EOV, should integrate omically-based measures of phylogenetic and functional diversity – and their derived products – to report on marine ecosystem state, functioning, and health.
8. Support should be gathered for the development of autonomous devices which allow the collection of samples for omics, initially focused on collecting samples for processing on shore.

Citizen Science

Successful data collection over the range of scales necessary to detect marine biodiversity change globally and to identify underlying mechanisms will require expansion of currently underutilized methods. These include efforts such as citizen science (Amano et al., 2016; Stuart-Smith et al., 2017; Pandya and Dibner, 2018) and the incorporation of Traditional and Local Ecological Knowledge (Thurstan et al., 2015; Charnley and Carothers et al., 2017). Goals of citizen science activities include a more comprehensive understanding of changes and also more sustained monitoring efforts in remote and difficult to reach areas. Citizen science efforts on land have been very successful in filling information gaps on biodiversity through efforts such as bird counts (Amano et al., 2016).

While some well-supervised and quality-controlled citizen science programs focusing on aspects of marine biodiversity have been successful, such as the Reef Life Survey (Stuart-Smith et al., 2018), compared to terrestrial efforts these programs are still restricted in scope. These programs have tremendous potential that should be considered and explored. In the United States, the Office of National Marine Sanctuaries supports numerous citizen science efforts as part of its outreach programs[21]. BioBlitz events are popular all over the world, including among MBON partners participating in the Smithsonian-led MarineGEO[22], which is working to fill gaps in the systematic collection and sharing of long-term data in the coastal zone. BioBlitzes are intense periods of biological surveying in an attempt to record all the living species within a designated area.

Ocean Sampling Day is a global scientific campaign that takes place during the solstice on June 21st, when 600 citizen scientists collect seawater samples to analyze marine microbial biodiversity and function[23]; Ocean Sampling Day activities have included a citizen science component, "MyOSD" (Schnetzer et al., 2016).

[19] https://glomicon.org/
[20] http://atlantos-h2020.eu/
[21] https://sanctuaries.noaa.gov/involved/citizen-science.html
[22] https://marinegeo.si.edu/
[23] http://www.my-osd.org/

In the United Kingdom, the Capturing our Coast project[24] trained ∼3000 citizen scientists between 2015 and 2018 to record patterns of species distributions in intertidal zones in the United Kingdom.

Crowd-sourced efforts to record not just biological data but also physical data are nascent, but there are examples of highly successful programs, including the Cefas citizen science diver program[25] and Project Hermes[26]. Wright S. et al., 2016, amalgamated data from recreational diver computers to compare diver profiles with existing Sea Surface Temperature and CTD measurements, to demonstrate the utility of these profiles for monitoring. The NOAA Ocean Acidification Program is cross-validating citizen-collected data on ocean pH with sensor data in the northeastern United States. The Smartfin project is outfitting surfboards with sensors capable of recording temperature and ocean pH[27].

Artificial Intelligence

Artificial intelligence (AI) refers broadly to computer systems that "can sense their environment, think, learn, and act in response to what they sense and their programmed objectives" (World Economic Forum, 2018). Machine learning is a subset of AI encompassing methods that incorporate a broad range of prediction, dimension reduction, classification and clustering. Deep Learning is, in turn, a subset of machine learning, composed of a group of specific methodologies using multi-layered neural networks, for more complex classification and predictive decision-making often requiring less training than traditional methods. AI in recent years, using Deep Learning techniques, has demonstrated the ability to drive vehicles and dominate the most complex games, such as Go.

How does this relate to marine biodiversity observation? Traditional forms of statistics and machine learning for predicting the distributions of species has long been a mainstay of marine biogeography. However, one of the most time-consuming aspects of biological observation has been identifying species, historically requiring taxonomic experts. Deep learning techniques enable automated classification of species from a variety of platforms, including: opportunistic citizen science visual observations (e.g., redmap.org.au; iNaturalist.org; Pimm et al., 2015); benthic photo quadrats (BisQue; Rahimi et al., 2014, Fedorov et al., 2017, 2018); cabled video observatories (Marini et al., 2018); unmanned underwater vehicles (Qin et al., 2015; Sung et al., 2017); acoustic-sensing hydrophones (Dugan et al., 2015; McQuay et al., 2017); plankton-sensing flow cytometers (Göröcs et al., 2018); and satellite imagery (Guirado et al., 2018). Taxonomic experts are still very much needed for developing datasets as inputs to this modeling approach.

Using this technology, sensor platforms could stream data into Deep Learning classifiers that produce species classifications with confidence metrics, such that high-confidence species classifications could then populate observational archives, such as OBIS, in real-time. Deploying these automated classification techniques across the wide range of available platforms promises to massively augment our ability to observe marine species.

Beyond simply detecting species, AI could be used to discern sex and age of organisms in the environment or diseases that may be affecting them (Rossi, 2017). Similar to self-driving vehicle applications, AI can improve navigation of unmanned underwater vehicles (Zhang et al., 2017; Cheng and Zhang, 2018). Even more broadly, AI has many potential applications to promote healthy oceans, including: sustainable fishing, preventing pollution, protecting habitats and species, as well as monitoring and mitigating impacts from climate change (including acidification) (World Economic Forum, 2018).

Critical needs in this new emerging area include (Hazen and Bromberg, 2018):

1. Framing of the questions that machine learning and deep learning can tackle – what hypotheses can be tested?
2. Highlighting exploratory questions—what are the specific opportunities we need to address first?
3. Identifying the most important feature in a natural system, including those that humans may have overlooked.
4. Conditioning the data for integration – some are spatial, such as vector point data and some are interpolated.
5. Knowing what tools to use, and when or how to use them (e.g., random forests, deep neural networks, convolutional neural networks, etc.).
6. Training datasets with accurate labels.

Ecological Marine Unit Classifications

Multiple approaches have been considered to classify marine ecosystems. Marine ecoregions (Spalding et al., 2007) represent an approach to classify coastal and shelf regions that has been widely used. The Global Environment Facility (GEF) has adopted the Large Marine Ecosystem concept as a framework to organize and implement ecosystem-scale resource assessment and management in coastal waters[28]. Here we describe in more depth the Ecological Marine Unit (EMU) approach, but the complementary nature of these and other efforts must be considered.

Ecological Marine Units represent a new approach for stratifying and classifying marine ecosystems at a global scale (Sayre et al., 2017). EMUs were commissioned in 2015 by GEO as a standardized, practical global ecosystems classification and map for the oceans; they are a key outcome of GEO BON and a recent contribution to MBON. The EMU project is one of four components of the new GEO Ecosystems Initiative within the GEO 2016 Transitional Work plan, for eventual use by the Global Earth Observation System of Systems (GEOSS). EMUs are comprised of a global point mesh framework, created from 52,487,233 points from the NOAA World Ocean Atlas; spatial resolution is 1/4° by 1/4° by varying depth; temporal resolution is currently decadal; each point has x, y, z, as well as six attributes of chemical and physical oceanographic structure (temperature,

[24]https://www.capturingourcoast.co.uk

[25]https://www.cefas.co.uk/cefas-data-hub/dois/cefas-citizen-science-diver-recorded-temperatures/

[26]https://cousteaudivers.wordpress.com/2018/04/04/project-hermes/

[27]https://smartphin.org/our-ocean/

[28]https://www.thegef.org/topics/large-marine-ecosystems

salinity, dissolved oxygen, nitrate, silicate, phosphate) that are likely drivers of many ecosystem responses. Sayre et al. (2017) implemented a new variation of k-means statistical clustering of the point mesh (using the pseudo-F statistic to help determine the numbers of clusters), allowing us to identify and map 37 environmentally distinct 3D regions within the water column. These units can be described according to their productivity, direction and velocity of currents, species abundance, global seafloor geomorphology (Harris et al., 2014), and much more. A series of data products for open access share the 3D point mesh and EMU clusters at the surface, bottom, and within the water column (**Figure 4**), as well as 2D web apps for exploration of the EMUs and the original World Ocean Atlas data[29] (Wright D.J. et al., 2016).

Many cite the need to scale this global framework down regionally and up temporally. Hence, over 15 teams of researchers are implementing EMUs in regional use cases, based on their own higher-resolution data for a richer geospatial accounting framework and visualization of species distributions. Among these are use cases in temperate upwelling, shallow subtropical and polar regions, where boundaries of surface seascapes are compared to surface EMUs, and at seasonal scales (Kavanaugh et al., 2018). The EU-funded ATLAS project[30] is comparing EMUs to species-based biogeographic clusters of Vulnerable Marine Ecosystems in the North Atlantic to refine UNESCO's Global Open Ocean and Deep Seafloor effort for this region. German researchers compiling 5000–6000 deep-sea distribution records from expeditions to the Sea of Okhotsk, the Aleutian Trench, and the Kuril-Kamchatka Trench (e.g., Brandt et al., 2015) are comparing their EMU use case with the ATLAS use case. Another use case seeks to add data on Northeast Pacific, Puget Sound and Southern California Bight carbonate chemistry and how it relates to *in situ* responses of an ocean acidification indicator, such as pteropoda shell dissolution and stress responses and thresholds (e.g., Bednaršek et al., 2017; Bednaršek et al., in revision) to the EMU 3-D point mesh network to examine responses of ecosystems to influences such as ocean acidification and thermal stress. EMUs may have potential to be closely linked to habitat suitability to describe broader patterns of ocean health.

[29]http://www.esri.com/ecological-marine-units

[30]https://www.eu-atlas.org

Validating EMUs for the Deep Sea

The study of vulnerable marine ecosystems (VMEs) biogeography has received limited attention, mainly due to the difficulties of collecting benthic data from deep-water environments—especially in large areas far from land—and the costs associated to these explorations. However, many VMEs lie in areas beyond national jurisdiction (ABNJs) where their distribution and driving factors of occurrence remain poorly understood. Biogeographic classifications have been used to analyze patterns of marine biodiversity and advance knowledge of evolutionary and ecosystem processes, even when information is sparse in certain areas (Rice et al., 2011). Biogeographic classifications can also assist governments in designing area based management tools (ABMT), such as marine protected areas, that might lead to better ocean governance in a future ocean challenged by rapid rates of climate change and increased exploitation of living and non-living resources in the deep ocean.

The Global Open Oceans and Deep Seabed (GOODS) is a biogeographic classification system for the deep ocean (UNESCO, 2009; Watling et al., 2013) based entirely on physical proxies, presumed to reflect species biogeography. GOODS divides the deep ocean into pelagic and benthic biogeographic provinces based on biological data such as primary production, and a range of environmental variables. Other emerging biogeographic classification schemes covering all marine regions, such as the EMUs, generally converge to the same proposed

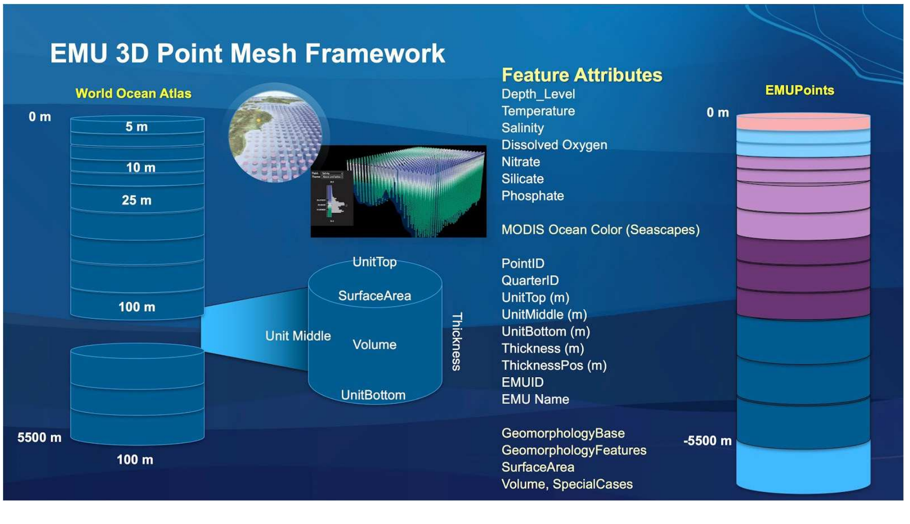

FIGURE 4 | The EMU is comprised of a global point mesh framework, created from the NOAA World Ocean Atlas. Each point includes attributes of chemical and physical oceanographic structure that are likely drivers of many ecosystem responses.

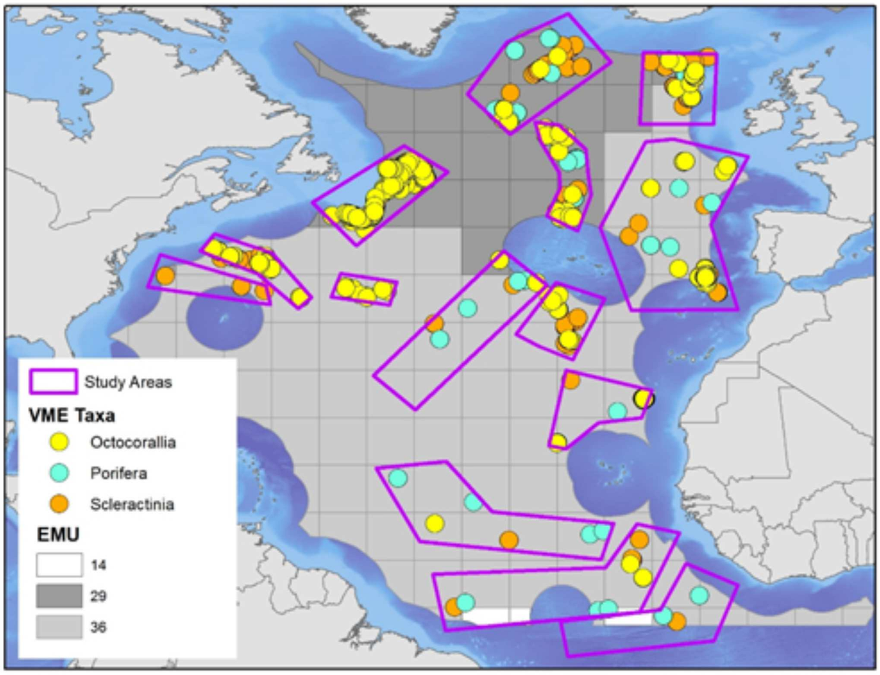

FIGURE 5 | EMUs were compared to species-based biogeographic clusters of vulnerable marine ecosystems (VMEs) in the North Atlantic. Three main VME-forming groups were selected: sponges (Porifera), stony corals (Scleractinia), and soft corals (Octocorallia).

biogeographic units in ABNJs. However, neither EMUs or GOODS are grounded in species data, nor have they been validated for complex habitats formed by VME indicator taxa.

The North Atlantic is a relatively young ocean that potentially offers the longest history of studying VME species, helping to understand VME biogeography. Heavy human exploitation (e.g., fisheries, renewables, oil and gas, deep-sea mining) and a rapidly changing climate (Rahmstorf et al., 2015) amplify the need to bring conservation efforts to this region. To help refine the GOODS biogeographic classification and validate EMUs for benthic species, EMUs were compared to species-based biogeographic clusters of VMEs in the North Atlantic.

Distribution data from VME species were compiled from published and unpublished data during the ATLAS project. Three main VME-forming groups were selected: sponges (Porifera), stony corals (Scleractinia) and soft corals (Octocorallia). Records were sparse (**Figure 5**), thus species data were aggregated into polygons, each polygon assigned to the EMU that was underneath it, and the original EMUs at 0.5° cell grid resolution were re-sampled to generate EMUs at 5° square cells. A distance matrix using Sorensen's coefficient was created based on species similarities between polygons, and used to produce biogeographic clusters using the unweighted pair-group method with arithmetic averages (UPGMA) algorithm. Significant differences in species compositions between polygons were assessed using analysis of variance (ANOSIM). Briefly, no statistical differences were found, indicating that representations of deep-sea VME biogeography using physical proxies do not adequately reflect species-level biogeographic patterns (**Table 1**).

THE NEXT FRONTIER: BENEFITS AND RECOMMENDATIONS

Advancing shared objectives toward the systematic, sustained and routine integration of biology into the global ocean observing system will bring additional important benefits, including: (1) expanding knowledge on the links among the marine environment, marine life, and the services the ocean provides; (2) coordination of disaggregated biodiversity and indicator monitoring and science programs to share data, experiences, knowledge, and standardized protocols; (3) increased understanding of physical, biological, chemical, climate, and anthropogenic drivers and their combined effects on ecosystem health; (4) enhanced capacity for forecasting of marine biodiversity and ecosystem health under future scenarios; (5) efficiency and optimized costs for data management and improved access to information; and (6) a framework for countries to establish biodiversity baselines and indicators to inform future assessments.

TABLE 1 | Statistical analysis of representations of deep-sea VME biogeography using physical proxies.

VME Taxa	*R*-value	*p*-value ($p < 0.005$)
Porifera	0.04938	0.516
Scleractinia	−0.025	0.505
Octocorallia	0.2625	0.073

As noted previously, the Ocean Obs 09 conference established the Framework for Ocean Observing, which recommends that observing system development be science-driven, informed by societal needs, and iterative – using a feedback loop whereby system requirements and outputs (tools, products, services) are evaluated to ensure the system is meeting user requirements. Ten years later, we still endeavor to establish a sustained biological ocean observing capability that is integrated with GOOS approaches and systems and will enhance our understanding of life in the ocean and our ability to protect ocean resources while supporting robust, resilient economies and communities.

Ocean Obs 19 presents an opportunity to focus the dialogue around relevance of MBON, OBIS, and the GOOS Biology and Ecosystems Panel to JCOMM Observation Coordination Group activities. It is a key mechanism to inform future plans for GOOS, including development of GOOS Regional Alliances. The MBON partnership with GOOS and OBIS ensures a practical focus for development of a globally coordinated, sustained ocean observing system. MBON also works with the IOC's Ocean Best Practices group[31]. MBON further works with global consortia focused on specific taxonomic groups or methodological approaches to biological observing (e.g., the global Continuous Plankton Recorder Survey, animal tracking networks). These groups are participating in the global dialogue and are together leading a community of scientists, managers, practitioners and users toward a common vision to build a sustained, coordinated, global ocean system of marine biological and ecosystem observations. Delivering the resulting information through an open access, integrated and quality-controlled database will support management decisions and address relevant science and societal needs.

Based on success of Ocean Obs 09, we encourage Ocean Obs 19 to endorse and advance the grass-roots and expanding effort embodied by MBON. In parallel, Ocean Obs 19 sponsors can promote a sustained, fit-for-purpose biological component of GOOS that leverages existing multi-disciplinary and multisectoral partnerships; integrates biology with physical and biogeochemical ocean observations; maximizes access to data and information products; and supports real-time needs for ecosystem-based assessment and management of marine fisheries, protected species, and special places. This has broad relevance for global policy drivers and priorities, as ecosystem-based assessments can be combined with socio-economic information to answer questions about economic, social and environmental impacts and sustainability. It is the only way to enable reporting mechanisms linked to the UN Sustainable Development Goals (particularly SDGs 14, 13, 15, 6, 2) as well as regional monitoring systems.

CONCLUSION

There is a real and present need for marine biological and biodiversity information to ensure wise and sustainable uses of the ocean. The Marine Biodiversity Observing Network of GEO provides a mechanism to bring together our global ocean observing community around the design and implementation of an integrated system to collect concurrent biological, biogeochemical and physical time series for marine life and relevant social and economic indicators of the status of humanity. Enabling such observations requires technology transfer between nations and groups, sharing of information, capacity building, and voluntary participation of citizens in biodiversity monitoring, providing standardized data useful for scientific analysis. All nations will benefit from a fit-for-purpose and sustainable observing system that improves our collective understanding of how life in the ocean is changing across spatial and temporal scales.

[31] http://www.oceanbestpractices.org/

AUTHOR CONTRIBUTIONS

GC, PB, AB, EM, HS, and DW contributed to the conception and design of the manuscript and provided the foundation for the manuscript development. GC led development and organization of the manuscript with much assistance from PB, AB, EM, FM-K, and BH. All authors contributed substantive content, supported multiple manuscript revisions, and read and approved the submitted version.

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REFERENCES

Aguiar-Pulido, V., Huang, W., Suarez-Ulloa, V., Cickovski, T., Mathee, K., and Narasimhan, G. (2016). Metagenomics, metatranscriptomics, and metabolomics approaches for microbiome analysis. *Evol. Bioinform.* 12(Suppl. 1), 5–16. doi: 10.4137/EBO.S36436

Amano, T., Lamming, J. D. L., and Sutherland, W. J. (2016). Spatial gaps in global biodiversity information and the role of citizen science. *Bioscience* 66, 393–400. doi: 10.1093/biosci/biw022

Andruszkiewicz, E. A., Starks, H. A., Chavez, F. P., Sassoubre, L. M., Block, B. A., and Boehm, A. B. (2017). Biomonitoring of marine vertebrates in Monterey Bay using eDNA metabarcoding. *PLoS One* 12:e0176343. doi: 10.1371/journal.pone.0176343

Apprill, A. (2017). Marine animal microbiomes: toward understanding host–microbiome interactions in a Changing Ocean. *Front. Mar. Sci.* 4:222

Austin, M. (2007). Species distribution models and ecological theory: a critical assessment and some possible new approaches. *Ecol. Model.* 200, 1–19 doi: 10.1016/j.ecolmodel.2006.07.005

Bates, A. E., Helmuth, B., Burrows, M. T., Duncan, M. I., Garrabou, J., Guy-Haim, T., et al. (2018). Biologists ignore ocean weather at their peril. *Nature* 560, 299–301. doi: 10.1038/d41586-018-05869-5

Bednaršek, N.; Harvey, C. J., McCabe, R. M., Tolimieri, N., and Klinger, T. (2017). New Ocean, new needs: application of pteropod shell dissolution as a biological indicator for marine resource management. *Ecol. Indic.* 76, 240–244. doi: 10.1016/j.ecolind.2017.01.025

Benedetti-Cecchi, L., Crowe, T., Boehme, L., Boero, F., Christensen, A., Grémare, A., et al. (2018). "Strengthening Europe's capability in biological ocean observations," in *Future Science Brief 3 of the European Marine Board*, eds Á. Muñiz Piniella, P. Kellett, K. Larkin, and J. J. Heymans (Ostend: European Marine Board), 2593–5232.

Benson, A., Brooks, C. M., Canonico, G., Duffy, E., Muller-Karger, F., Sosik, H. M., et al. (2018). Integrated observations and informatics improve understanding of changing marine ecosystems. *Front. Mar. Sci.* 5:428. doi: 10.3389/fmars.2018.00428

Bierlich, K., Miller, C., DeForce, E., Friedlaender, A. S., Johnston, D. W., and Apprill, A. (2017). Temporal and regional variability in the skin microbiome of humpback whales along the Western Antarctic Peninsula. *Appl. Environ. Microbiol.* 84:e02574-17. doi: 10.1128/AEM.02574-17.

Biller, S. J., Berube, P. M., Dooley, K., Williams, M., Satinsky, B. M., Hackl, T., et al. (2018). Marine microbial metagenomes sampled across space and time. *Sci. Data* 5:180176. doi: 10.1038/sdata.2018.176.

Boetius, A., Anesio, A. M., Deming, J. W., Mikucki, J. A., and Rapp, J. Z. (2015). Microbial ecology of the cryosphere: sea ice and glacial habitats. *Nat. Rev. Microbiol.* 13, 677–690. doi: 10.1038/nrmicro3522.

Boss, E., Waite, A., Muller-Karger, F., Yamazaki, H., and Wanninkhof, R., Uitz, J., et al. (2018). Beyond chlorophyll fluorescence: the time is right to expand biological measurements in ocean observing programs. *Limnol. Oceanogr. Bull.* 27, 89–90. doi: 10.1002/lob.10243

Bourne, D. G., Morrow, K. M., and Webster, N. S. (2016). Insights into the coral microbiome: underpinning the health and resilience of reef ecosystems. *Annu. Rev. Microbiol.* 70, 317–340. doi: 10.1146/annurev-micro-102215-095440

Brandt, A., Elsner, N. O., Malyutina, M. V., Brenke, N., Golovan, O. A., et al. (2015). Abyssal macrofauna of the Kuril–Kamchatka Trench area (Northwest Pacific) collected by means of a camera–epibenthic sledge. *Deep Sea Res. Part II* 111: 175–187. doi: 10.1016/j.dsr2.2014.11.002.

Brownlee, E. F., Olson, R. J., and Sosik, H. M. (2016). Microzooplankton community structure investigated with imaging flow cytometry and automated live-cell staining. *Mar. Ecol. Prog. Ser.* 550, 65–81. doi: 10.3354/meps11687

Butchart, S. H., Walpole, M., Collen, B., van Strien, A., Scharlemann, J. P., Almond, R. E., et al. (2010). Global biodiversity: indicators of recent declines. *Science* 328, 1164–1168. doi: 10.1126/science.1187512

Buttigieg, P. L., Fadeev, E., Bienhold, C., Hehemann, L., Offre, P., and Boetius, A. (2018). Marine microbes in 4D — using time series observation to assess the dynamics of the ocean microbiome and its links to ocean health. *Curr. Opin. Microbiol.* 43, 169–185. doi: 10.1016/j.mib.2018.01.015.

Castillo, K. D., and Lima, F. P. (2010). Comparison of *in situ* and satellite-derived (MODIS-Aqua/Terra) methods for assessing temperatures on coral reefs. *Limnol. Oceanogr. Methods* 8, 107–117. doi: 10.4319/lom.2010.8.0107

Charnley, S., and Carothers, C., Satterfield, T., Levine, A., Poe, M. R., Norman, K., Donatuto, J., Breslow, S. J., et al. (2017). Evaluating the best available social science for natural resource management decision-making. *Environ. Sci. Policy* 73, 80–88. doi: 10.1016/j.envsci.2017.04.002

Chaudhary, C., Saeedi, H., and Costello, M. J. (2017). Marine species richness is bimodal with latitude: a reply to Fernandez and Marques. *Trends Ecol. Evol.* 32, 234–237. doi: 10.1016/j.tree.2017.02.007

Chavez, F. P., Ryan, J., lluch-Cota, S. E., and Ñiquen, C. M. (2003). From Anchovies to Sardines and Back: multidecadal change in the Pacific Ocean. *Science* 299, 217–221, doi: 10.1126/science.1075880

Cheng, Y., and Zhang, W. (2018). Concise deep reinforcement learning obstacle avoidance for underactuated unmanned marine vessels. *Neurocomputing* 272, 63–73. doi: 10.1016/j.neucom.2017.06.066

Cordier, T., Esling, P., Lejzerowicz, F., Visco, J., Ouadahi, A., Martins, C., et al. (2017). Predicting the ecological quality status of marine environments from eDNA metabarcoding data using supervised machine learning. *Environ. Sci. Technol.* 51, 9118–9126.

Cortés, J., Oxenford, H. A., van Tussenbroek, B. I., Jordán-Dahlgren, E., Cróquer, A., Bastidas, C., et al. (2019). The CARICOMP Network of Caribbean marine laboratories (1985–2007): history, key findings, and lessons learned. *Front. Mar. Sci.* 5:519. doi: 10.3389/fmars.2018.00519.

Cowen R. K., and Guigand, C. M. (2008). *In situ* Ichthyoplankton Imaging System (ISIIS): system design and preliminary results. *Limnol. Oceanogr. Methods.* 6:126–132. doi: 10.4319/lom.2008.6.126

Cruz, M., Gabor, N., Mora, E., Jiménez, R., and Mair, J. (2003). The known and unknown about marine biodiversity in Ecuador (continental and insular). *Gayana* 67, 232–260.

Davies, N., Field, D., Amaral-Zettler, L., Clark, M. S., Deck, J., Drummond, A., et al. (2014). The founding charter of the genomic observatories network. *Gigascience* 3:2.

Davies, T., Maxwell, S., Kaschner, K., Garilao, C., and Ban, N. (2017). Large marine protected areas represent biodiversity now and under climate change. *Nat. Sci. Rep.* 7:9569. doi: 10.1038/s41598-017-08758-5.

De Pooter, D., Appeltans, W., Bailly, N., Bristol, S., Deneudt, K., Eliezer, M., et al. (2017). Toward a new data standard for combined marine biological and environmental datasets-expanding OBIS beyond species occurrences. *Bio. Data J.* 5:e10989. doi: 10.3897/BDJ.5.e10989

Deck, J., Gaither, M. R., Ewing, R., Bird, C. E., Davies, N., Meyer, C., et al. (2017). The genomic observatories metadatabase (GeOMe): a new repository for field and sampling event metadata associated with genetic samples. *PLoS Biol.* 15:e2002925. doi: 10.1371/journal.pbio.2002925.

Djurhuus, A., Pitz, K., Sawaya, N., Rojas-Márquez, J., Michaud, B., and Montes, E. et al. (2018). Evaluation of marine zooplankton community structure through environmental DNA metabarcoding. *Limnol. Oceanogr. Methods* 16, 209–221.

Djurhuus, A., Port, J., Closek, C. J., Yamahara, K. M., Romero-Maraccini, O., and Walz, K. R., et al. (2017). Evaluation of filtration and DNA extraction methods for environmental DNA biodiversity assessments across multiple trophic levels. *Front. Mar. Sci.* 4:314

Dubilier, N., McFall-Ngai, M., and Zhao, L. (2015). Microbiology: create a global microbiome effort. *Nature* 526, 631–634. doi: 10.1038/526631a

Dugan, P. J., Clark, C. W., LeCun, Y. A., and Van Parijs, S. M. (2015). *DCL System Using Deep Learning Approaches for Land-Based or Ship-Based Real Time Recognition and Localization of Marine Mammals. Bioacoustics Research Program, Cornell University Ithaca United States*. Available at: http://www.dtic.mil/docs/citations/AD1014344 (accessed November 2018).

Escribano, R., Fernández, M., and Aranís, A. (2003). Physical-chemical processes and patterns of diversity of the Chilean eastern boundary pelagic and benthic marine ecosystems: an overview. *Gayana* 67, 190–205.

Fahner, N., McCarthy, A., Barnes, J., Singer, G., and Hajibabaei, M. (2018). Experimental design considerations for assessing marine biodiversity using environmental DNA. *PeerJ. Prepr.* 6:e26814v1.

Fedorov, D., Kvilekval, K., Doheny, B., Sampson, S., Miller, R., and Manjunath, B. S. (2017). *Deep Learning for all: Managing and Analyzing Underwater and Remote Sensing Imagery on the web Using BisQue*. Available at: https://escholarship.org/uc/item/9z73t7hv (accessed November 2018).

Fedorov, D., Manjunath, B. S., Lang, C. A., and Kvilekval, K. (2018). Chapter 9 - Scalable image informatics. in R. Chellappa and S. Theodoridis (Eds.), *Academic Press Library in Signal Processing*, Vol. 6 (347–364). Academic Press: Cambridge. doi: 10.1016/b978-0-12-811889-4.00009-9

Field, D., Amaral-Zettler, L., Cochrane, G., Cole, J. R., Dawyndt, P., Garrity, G. M., et al. (2011). The genomic standards consortium. *PLoS Biol.* 9:e1001088. doi: 10.1371/journal.pbio.1001088

Geller, G. N., Halpin, P. N., Helmuth, B., Hestir, E. L., Skidmore, A., and Abrams, M. J., et al. (2017). Remote sensing for biodiversity, in *The GEO Handbook on Biodiversity Observation Networks*, eds M. Walters and R. J. Scholes, Berlin: Springer.

Goodwin, K. D., Muller-Karger, F. E., Djurhuus, A., Zeigler Allen, L., Allen, A. E., McCrow, J. P., et al. (2019). "Molecular approaches for an operational marine biodiversity observation network," in *World Seas: an Environmental Evaluation*, ed. C. Sheppard (Amsterdam: Elsevier), 613–631. doi: 10.1016/b978-0-12-805052-1.00032-2

Goodwin, K. D., Thompson, L. R., Duarte, B., Kahlke, T., Thompson, A. R., Marques, J. C., et al. (2017). DNA Sequencing as a tool to monitor marine ecological status. *Front. Mar. Sci.* 4, 1–14. doi: 10.3389/fmars.2017.00107

Guirado, E., Tabik, S., Rivas, M. L., Alcaraz-Segura, D., and Herrera, F. (2018). Automatic whale counting in satellite images with deep learning. *BioRxiv*. doi: 10.1101/443671

Göröcs, Z., Tamamitsu, M., Bianco, V., Wolf, P., Roy, S., Shindo, K., et al. (2018). A deep learning-enabled portable imaging flow cytometer for cost-effective, high-throughput, and label-free analysis of natural water samples. *Light Sci. Appl.* 7:66. doi: 10.1038/s41377-018-0067-0

Hamaguchi, M., Shimabukuro, H., Hori, M., Yoshida, G., Terada, T., and Miyajima, T. (2018). Quantitative real-time polymerase chain reaction (PCR) and droplet digital PCR duplex assays for detecting Zostera marina DNA in coastal sediments. *Limnol. Oceanogr. Methods* 16, 253–264. doi: 10.1002/lom3.10242

Harris, P. T., Macmillan-Lawler, M., Rupp, J., and Baker, E. K. (2014). Geomorphology of the oceans. *Mar. Geol.* 352, 4–24. doi: 10.1016/j.margeo.2014.01.011

Hazen, R. M., and Bromberg, Y. (2018). *4D Workshop: Deep-time Data Driven Discovery and the Evolution of Earth*. Washington, DC: Carnegie Institution of Science.

Helmuth, B. (2009). From cells to coastlines: how can we use physiology to forecast the impacts of climate change? *J. Exp. Biol.* 212, 753–760. doi: 10.1242/jeb.023861

Helmuth, B. S., Harley, C. D. G., Halpin, P.,O'Donnell, M., Hofmann, G. E.,and Blanchette, C. (2002). Climate change and latitudinal patterns of intertidal thermal stress. *Science* 298:1015–1017 doi: 10.1126/science.1076814

Hofmann, G. E., Smith, J. E., Johnson, K. S., Send, U., Levin, L. A., and Micheli, F. et al. (2011). High-frequency dynamics of ocean pH: a multi-ecosystem approach. *PLoS One* 6:e28983. doi: 10.1371/journal.pone.0028983

Hui, C., Foxcroft, L. C., Richardson, D. M., and MacFadyen, S. (2011). Defining optimal sampling effort for large-scale monitoring of invasive alien plants: a Bayesian method for estimating abundance and distribution. *J. Appl. Ecol* 48, 768–776. doi: 10.1111/j.1365-2664.2011.01974.x

Hunter-Cevera, K. R., Neubert, M. G., Olson, R. J., Solow, A. R., Shalapyonok, A., Sosik, H. M., et al. (2016). Physiological and ecological drivers of early spring blooms of a coastal phytoplankter. *Science* 354, 326–329. doi: 10.1126/science.aaf8536

Karl, D. M., and Church, M. J. (2014). Microbial oceanography and the hawaii ocean time-series programme. *Nat. Rev. Microbiol.* 12, 699–713. doi: 10.1038/nrmicro3333

Karsenti, E., Acinas, S. G., Bork, P., Bowler, C., De Vargas, C., Raes, J., et al. (2011). A holistic approach to marine eco-systems biology. *PLoS Biol.* 9:e1001177. doi: 10.1371/journal.pbio.1001177

Kaschner, K., Kesner-Reyes, K., Garilao, C., Rius-Barile, J., Rees, T., and Froese, R. (2016). *AquaMaps: Predicted Range Maps for Aquatic Species. World Wide Web Electronic Publication*. Available at: www.aquamaps.org, Version 08/2016 (accessed November 2018).

Kavanaugh, M., Iken, K., Grebmeier, J., Otis, D., Muller-Karger, F., Montes, E., et al. (2018). "Monitoring and predicting Arctic marine biodiversity across dynamic seascapes," in *Proceedings of The 4th World Conference on Marine Biodiversity*, Montreal 13–16.

Kopf, A., Bicak, M., Kottmann, R., Schnetzer, J., Kostadinov, I., Lehmann, K., et al. (2015). The ocean sampling day consortium. *Gigascience* 4:27. doi: 10.1186/s13742-015-0066-5

Kroeker, K. J., Sanford, E., Rose, J. M., Blanchette, C. A., Chan, F., Chavez, F. P., et al. (2016). Interacting environmental mosaics drive geographic variation in mussel performance and species interactions. *Ecol. Lett.* 19, 771–779. doi: 10.1111/ele.12613

Leichter, J. J., Helmuth, B., and Fischer, A. M. (2006). Variation beneath the surface: quantifying complex thermal environments on coral reefs in the Caribbean, Bahamas and Florida. *J. Mar. Res.* 64, 563–588. doi: 10.1357/002224006778715711

Levin, P., and Poe, M. (2017). *Conservation for the Anthropocene Ocean: Interdisciplinary Science in Support of Nature and People*. Cambridge: Academic Press, 530.

Lindstrom, E., Gunn, J., Fischer, A., McCurdy, A., and Glover, L. K. (2012). *A Framework for Ocean Observing. By the Task Team for an Integrated Framework for Sustained Ocean Observing*. Paris: UNESCO

Lombard, F., Boss, E., Waite, A. M., Vogt, M., Uitz, J., Stemmann, L., et al. (2019). Globally consistent quantitative observations of planktonic ecosystems. *Front. Mar. Sci*. 6:196. doi: 10.3389/fmars.2019.00196

Marini, S., Fanelli, E., Sbragaglia, V., Azzurro, E., Fernandez, J. D. R., and Aguzzi, J. (2018). Tracking fish abundance by underwater image recognition. *Sci. Rep.* 8:13748. doi: 10.1038/s41598-018-32089-8

McQuay, C., Sattar, F., and Driessen, P. F. (2017). "Deep learning for hydrophone big data," in *Proceedings of the 2017 IEEE Pacific Rim Conference on Communications, Computers and Signal Processing (PACRIM)*, Victoria, BC.

Miloslavich, P., Bax, N. J., Simmons, S. E., Klein, E., Appeltans, W., Aburto-Oropeza, O., et al. (2018a). Essential ocean variables for global sustained observations of biodiversity and ecosystem changes. *Glob. Chang Biol.* 24, 2416–2433. doi: 10.1111/gcb.14108

Miloslavich, P., Seeyave, S., Ali, E., Bax, N., Delgado, C., Evers-King, H., et al. (2018b). Challenges for global ocean observation: the need for increased human capacity. *J. Oper. Oceanogr.* 1–12. doi: 10.1080/1755876X.2018.1526463

Miloslavich, P., Cruz-Motta, J. J., Hernandez, A., Herrera, C. A., Klein, E., Barros, F., et al. (2016) "Benthic assemblages in South American intertidal rocky shores: biodiversity, services, and threats," in *Marine Benthos: Biology, Ecosystem Functions and Environmental Impact* Ed, R. R. Rodríguez (Hauppauge, NY: Nova Science Publishers).

Miloslavich, P., Klein, E., Díaz, J. M., Hernández, C. E., Bigatti, G., Campos, L., et al. (2011). Marine biodiversity in the atlantic and pacific coasts of south america: knowledge and gaps. *PLoS One* 6:e14631. doi: 10.1371/journal.pone.0014631

Mislan, K. A. S., and Wethey, D. S. (2011). Gridded meteorological data as a resource for mechanistic macroecology in coastal environments. *Ecol. Appl.* 21, 2678–2690. doi: 10.1890/10-2049.1

Moran, M. A. (2015). The global ocean microbiome. *Science* 350:aac8455. doi: 10.1126/science.aac8455

Muller-Karger, F. E., Astor, Y. M., Benitez-Nelson, C. R., Buck, K. N., Fanning, K. A., Lorenzoni, L., et al. (2019). The scientific legacy of the CARIACO ocean time-series program. *Ann. Rev. Mar. Sci.* 11, 413–427.

Muller-Karger, F. E., Kavanaugh, M. T., Montes, E., Balch, W. M., Breitbart, M., Chavez, F. P., et al. (2014). A framework for a marine biodiversity observing network within changing continental shelf seascapes. *Oceanography* 27, 18–23. doi: 10.5670/oceanog.2014.56

Muller-Karger, F E., Hestir, E., Ade, C., Turpie, K., Roberts, D., Siegel, D., et al. (2018a). Satellite sensor requirements for monitoring essential biodiversity variables of coastal ecosystems. *Ecol. Appl.* 28, 749–760.

Muller-Karger, F. E., Miloslavich, P., Bax, N., Simmons, S., Costello, M. J., Pinto, I. S., et al. (2018b). Advancing marine biological observations and data requirements of the complementary essential ocean variables (EOVs) and essential biodiversity variables (EBVs) frameworks. *Front. Mar. Sci.* 5:211. doi: 10.3389/fmars.2018.00211

Neiva, J., Serrão, E. A., Anderson, L., Raimondi, P. T., Martins, N., Gouveia, L., et al. (2017). Cryptic diversity, geographical endemism and allopolyploidy in NE Pacific seaweeds. *BMC Evol. Biol.* 17:30. doi: 10.1186/s12862-017-0878-2

Nilsson, R. H., Larsson, K. -H., Taylor, A. F. S., Bengtsson-Palme, J., Jeppesen, T. S., Schigel, D., et al. (2018). The UNITE database for molecular identification of fungi: handling dark taxa and parallel taxonomic classifications. *Nucleic Acids Res.* 47, D259–D264. doi: 10.1093/nar/gky1022

Österblom, H., Crona, B. I., Folke, C., Nyström, M., and Troell, M. (2017). Marine ecosystem science on an intertwined planet. *Ecosystems* 20, 54–61. doi: 10.1007/s10021-016-9998-6

Pacifici, M., Foden, W. B., Visconti, P., Watson, J. F. M., Butchart, S. H. M., Kovacs, K. M., et al. (2015). Assessing species vulnerability to climate change. *Nat. Clim. Change* 5, 215–225.

Pandya, R. E., and Dibner, K. A. (2018). *Learning Through Citizen Science: Enhancing Opportunities by Design*. Washington, DC: National Academies Press.

Pawlowski, J., Kelly-Quinn, M., Altermatt, F., Apothéloz-Perret-Gentil, L., Beja, P., Boggero, A., et al. (2018). The future of biotic indices in the ecogenomic era: integrating (e)DNA metabarcoding in biological assessment of aquatic ecosystems. *Sci. Total Environ.* 637–638, 1295–1310. doi: 10.1016/j.scitotenv.2018.05.002

Pearlman, J., Buttigieg, P. L., Simpson, P., Heslop, E. E., Munoz, C., Bushnell, M., et al. (2018). "Accessing Existing and Emerging Best Practices for Ocean Observation, a new approach for end-to-end management of Best Practices," in *Proceedings of the Oceans'17, Anchorage: Conference, MTS/IEEE*. (Anchorage: IEEE).

Pereira, H. M., Ferrier, S., Walters, M., Geller, G. N., Jongman, R. H. G., Scholes, R. J., et al. (2013). Essential biodiversity variables. *Science* 339. 277–278.

Pesant, S., Grigorov, I., Malfatti, F., Magalhães, C., Vezzi, A., Poulain, J., et al. (2017). *EMOSE (2017) Inter-Comparison of Marine Plankton Metagenomic Analysis Methods*. Peoria, IL: OSF.

Picheral, M., Guidi, L., Stemmann, L., Karl, D. M., Iddaoud, G., and Gorsky, G. (2010). The underwater vision profiler 5: an advanced instrument for high spatial resolution studies of particle size spectra and zooplankton. *Limnol. Oceanogr. Methods* 8, 462–473. doi: 10.4319/lom.2010.8.462

Pimm, S. L., Alibhai, S., Bergl, R., Dehgan, A., Giri, C., Jewell, Z., et al. (2015). Emerging technologies to conserve biodiversity. *Trends Ecol. Evol.* 30, 685–696. doi: 10.1016/j.tree.2015.08.008

Qin, H., Li, X., Yang, Z., and Shang, M. (2015). "When underwater imagery analysis meets deep learning: A solution at the age of big visual data," in *Proceedings of the OCEANS 2015 - MTS/IEEE Washington*, Washington, DC.

Rahimi, A. M., Miller, R. J., Fedorov, D. V., Sunderrajan, S., Doheny, B. M., Page, H. M., et al. (2014). "Marine Biodiversity Classification Using Dropout Regularization," in *Proceedings of the 2014 ICPR Workshop on Computer Vision for Analysis of Underwater Imagery*, Tockholm.

Rahmstorf, S., Box, J. E., Feulner, G., Mann, M. E., Robinson, A., Rutherford, S., et al. (2015). Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. *Nat. Clim. Change* 5, 475–480. doi: 10.1038/nclimate2554

Rice, J., Gjerde, K. M., Ardron, J., Arico, S., Cresswell, I., Escobar, E., et al. (2011). Policy relevance of biogeographic classification for conservation and management of marine biodiversity beyond national jurisdiction, and the GOODS biogeographic classification. *Ocean Coast. Manag.* 54, 110–122. doi: 10.1016/j.ocecoaman.2010.10.010

Rossi, R. E. (2017). Using inaturalist observations to detect disease in red mangroves (*Rhizophora mangle*). *PeerJ* 5:e3326v1

Rougier, T., Lassalle, G., Drouineau, H., Dumoulin, N., Faure, T., Deffuant, G., et al. (2015). The combined use of correlative and mechanistic species distribution models benefits low conservation status species. *PLoS One* 10:e0139194. doi: 10.1371/journal.pone.0139194

Rusch, D. B., Halpern, A. L., Sutton, G., Heidelberg, K. B., Williamson, S., Yooseph, S., et al. (2007). The sorcerer II global ocean sampling expedition: northwest atlantic through eastern tropical pacific. *PLoS Biol.* 5, 398–431.

Sayre, R. G., Wright, D. J., Breyer, S. P., Butler, K. A., Van Graafeiland, K., Costello, M. J., et al. (2017). A three-dimensional mapping of the ocean based on environmental data. *Oceanography* 30, 90–103. doi: 10.5670/oceanog.2017.116

Schnetzer, J., Kopf, A., Bietz, M. J., Buttigieg, P. L., Fernandez-Guerra, A., Ristov, A. P., et al. (2016). MyOSD 2014: evaluating oceanographic measurements contributed by citizen scientists in support of ocean sampling day. *J. Microbiol. Biol. Educ.* 17, 163–171. doi: 10.1128/jmbe.v17i1.1001

Singer, A., Johst, K., Banitz, T., Fowler, M. S., Groeneveld, J., Gutiérrez, A. G., et al. (2016). Community dynamics under environmental change: how can next generation mechanistic models improve projections of species distributions? *Ecol. Model.* 326, 63–74. doi: 10.1016/j.ecolmodel.2015.11.007

Smale, D. A., and Wernberg, T. (2009). Satellite-derived SST data as a proxy for water temperature in nearshore benthic ecology. *Mar. Ecol. Prog. Ser.* 387, 27–37. doi: 10.3354/meps08132

Soltwedel, T., Schauer, U., Boebel, O., Nothig, E. M., Bracher, A., Metfies, K., et al. (2013). "FRAM - FRontiers in Arctic marine Monitoring Visions for permanent observations in a gateway to the Arctic Ocean," in *Proceedings of the OCEANS 2013 MTS/IEEE: The Challenges of the Northern Dimension*, Bergen.

Spalding, M. D., Fox, H. E., Allen, G. R., Davidson, N., Ferdana, Z. A., Finlayson, M., et al. (2007). Marine ecoregions of the world: a bioregionalization of coastal and shelf areas. *BioScience* 57, 573–583. doi: 10.1641/b570707

Stat, M., Huggett, M. J., Bernasconi, R., DiBattista, J. D., Berry, T. E., Newman, S. J., et al. (2017). Ecosystem biomonitoring with eDNA: metabarcoding across the tree of life in a tropical marine environment. *Sci. Rep.* 7:12240. doi: 10.1038/s41598-017-12501-5

Stat, M., John, J., DiBattista, J. D., Newman, S. J., Bunce, M., and Harvey, E. S. (2018). Combined use of eDNA metabarcoding and video surveillance for the assessment of fish biodiversity. *Conserv. Biol.* 33, 196–205. doi: 10.1111/cobi.13183

Staudinger, M. D., Carter, S. L., Cross, M. S., Dubois, N. S., Duffy, J. E., Enquist, C. A. F., et al. (2013). Biodiversity in a changing climate: a synthesis of current and projected trends in the US. *Front. Ecol. Environ.* 11, 465–473. doi: 10.1890/120272

Steinberg, D. K., Carlson, C. A., Bates, N. R., Johnson, R. J., Michaels, A. F., and Knap, A. H. (2001). Overview of the US JGOFS bermuda atlantic time-series study (BATS): a decade-scale look at ocean biology and biogeochemistry. *Deep Sea Res. Part II Top. Stud. Oceanogr.* 48, 1405–1447. doi: 10.1016/S0967-0645(00)00148-X

Stuart-Smith, R. D., Brown, C. J., Ceccarelli, D. M., and Edgar, G. J. (2018). Ecosystem restructuring along the great barrier reef following mass coral bleaching. *Nature* 560, 92–96. doi: 10.1038/s41586-018-0359-9

Stuart-Smith, R. D., Edgar, G. J., Barrett, N. S., Bates, A. E., Baker, S. C., Bax, N. J., et al. (2017). Assessing national biodiversity trends for rocky and coral reefs through the integration of citizen science and scientific monitoring programs. *Bioscience* 67, 134–146. doi: 10.1093/biosci/biw180

Sunagawa, S., Coelho, L. P., Chaffron, S., Kultima, J. R., Labadie, K., Salazar, G., et al. (2015). Structure and function of the global ocean microbiome. *Science* 348, 1261359–1261359. doi: 10.1126/science.1261359

Sung, M., Yu, S., and Girdhar, Y. (2017). "Vision based real-time fish detection using convolutional neural network," in *Proceedings of the OCEANS 2017 - Aberdeen*, Aberdeen.

Thompson, L. R., Sanders, J. G., McDonald, D., Amir, A., Ladau, J., Locey, K. J., et al. (2017). A communal catalogue reveals Earth's multiscale microbial diversity. *Nature* 551, 457–463. doi: 10.1038/nature24621

Thurstan, R. H., McClenachan, L., Crowder, L. B., Drew, J., AKittinger, J. N., Levin, P. S., et al. (2015). Filling historical data gaps to foster solutions in marine conservation. *Ocean Coast. Manag.* 115, 31–40. doi: 10.1016/j.ocecoaman.2015.04.019

UNESCO (2009). *Global Open Oceans and Deep Seabed (GOODS) - Biogeographic Classification*. IOC Technical Series 84. Paris: UNESCO.

UNESCO (2018). *Update on IOC Custodianship Role in Relation to SDG 14 Indicators. IOC/EC-LI/2 Annex 6*. Paris: UNESCO.

Watling, L., Guinotte, J., Clark, M. R., and Smith, C. R. (2013). A proposed biogeography of the deep ocean floor. *Prog. Oceanogr.* 111, 91–112. doi: 10.1016/j.pocean.2012.11.003

Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., Appleton, G., Axton, M., Baak, A., et al. (2016). The FAIR guiding principles for scientific data management and stewardship. *Sci. Data* 3:160018. doi: 10.1038/sdata.2016.18

Woodin, S. A., Hilbish, T. J., Helmuth, B., Jones, S. J., and Wethey, D. S. (2013). Climate change, species distribution models, and physiological performance metrics: predicting when biogeographic models are likely to fail. *Ecol. Evol.* 3, 3334–3346.

World Economic Forum (2018). *Harnessing Artificial Intelligence for the Earth. Fourth Industrial Revolution for the Earth Series*. Available at: http://www3.weforum.org/docs/Harnessing_Artificial_Intelligence_for_the_Earth_report_2018.pdf (accessed November 2018).

Wright, D. J. (2016). Toward a digital resilience. *Elem. Sci. Anth.* 4:000082. doi: 10.12952/journal.elementa.000082

Wright, D. J., Sayre, R., Breyer, S., Butler, K. A., and Van Graafeiland, K. (2016). *52 Million Points and Counting: A New Stratification Approach for Mapping Global Marine Ecosystems. Eos, Transactions American Geophysical Union*. San Francisco, CA: American Geophysical Union.

Wright, S., Hull, T., Sivyer, D. B., Pearce, D., Pinnegar, J. K., Sayer, M. D. J., et al. (2016). SCUBA divers as oceanographic samplers: the potential of dive computers to augment aquatic temperature monitoring. *Sci. Rep.* 6:30164. doi: 10.1038/srep30164

Zardi, G. I., Nicastro, K. R., Serrão, E. A., Jacinto, R., Monteiro, C. A., and Pearson, G. A. (2015). Closer to the rear edge: ecology and genetic diversity down the core-edgegradient of a marine macroalga. *Ecosphere* 6, 1–25.

Zhang, T., Li, Q., Zhang, C., Liang, H., Li, P., Wang, T., et al. (2017). Current trends in the development of intelligent unmanned autonomous systems. *Front. Inform. Technol. Electr. Eng.* 18, 68–85. doi: 10.1631/FITEE.1601650

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frontiers in Marine Science

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Model-Observations Synergy in the Coastal Ocean

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Integration of observations of the coastal ocean continuum, from regional oceans to shelf seas and estuaries/deltas with models, can substantially increase the value of observations and enable a wealth of applications. In particular, models can play a critical role at connecting sparse observations, synthesizing them, and assisting the design of observational networks; in turn, whenever available, observations can guide coastal model development. Coastal observations should sample the two-way interactions between nearshore, estuarine and shelf processes and open ocean processes, while accounting for the different pace of circulation drivers, such as the fast atmospheric, hydrological and tidal processes and the slower general ocean circulation and climate scales. Because of these challenges, high-resolution models can serve as connectors and integrators of coastal continuum observations. Data assimilation approaches can provide quantitative, validated estimates of Essential Ocean Variables in the coastal continuum, adding scientific and socioeconomic value to observations through applications (e.g., sea-level rise monitoring, coastal management under a sustainable ecosystem approach, aquaculture, dredging, transport and fate of pollutants, maritime safety, hazards under natural variability or climate change). We strongly recommend an internationally coordinated approach in support of the proper integration of global and coastal continuum scales, as well as for critical tasks such as community-agreed bathymetry and coastline products.

Keywords: coastal, ocean, observations, models, synergy, synthesis, assimilation, array design

INTRODUCTION

The main interface between humans and the ocean occurs in the coastal seas. Major marine industries thrive in this area while citizens make daily use of the coastal ocean for recreation. OceanPredict (formerly GODAE OceanView; Davidson et al., 2019) promotes the proper integration of all ocean scales under an international, operational, data-assimilative, multi-nested modeling framework. A Coastal Ocean Forecasting System (COFS), often targeted toward operational use, involves a combination of appropriate coastal observing and modeling systems (e.g., Kourafalou et al., 2015a; De Mey et al., 2017). The resulting value chain comprises observations made at sea, satellite data, ocean forecasts and analyses providing specific products and services for end users.

Observing systems tend to be spatiotemporally sparse in coastal regions, in comparison to the small scales of ecosystem variability found there. A crucial observational challenge is addressing the variety of important spatial and temporal scales of the coastal continuum, i.e., the seamless transition from the deep ocean to estuaries, through the shelf: observations should sample the multiscale, two-way interactions of estuarine, nearshore, and shelf processes with open ocean processes, while accounting for the different pace of circulation drivers, such as the fast atmospheric and tidal processes and the slower general ocean circulation and climate scales, and for gradients of biological production, from mesotrophic estuaries to oligotrophic oceans.

To fully realize the benefits of coastal observing systems, observations and models must be better integrated within COFS. Observations can be used to guide coastal model development and assessment (see section "Using Observations to Guide Coastal Model Development and Assessment"). In turn, models can be used to connect and interpret sparse coastal observations (see section "Using Models to Connect and Interpret Sparse Coastal Observations"). Data assimilation (DA) and machine learning (ML) can provide quantitative, validated estimates of Essential Ocean Variables and parameters in the coastal continuum (see section "Using Coastal Models to Synthesize Observations"). Models and DA can also be used to design and optimize existing and future observational arrays, with implications on sampling technology and networks (see section "Using Models to Design and Optimize Coastal Observing Systems").

Integration of observations with models can add value to coastal observations and enable a wealth of applications, e.g., monitoring coastal sea-level rise (Ponte et al., 2019), decision-making support, marine search and rescue, coastal management under a sustainable ecosystem approach, aquaculture, dredging, transport and fate of pollutants, port operations, maritime and coastal populations safety, hazard analysis under natural variability and climate change. This paper focusses on how science can support coastal operational monitoring and forecasting to that end.

USING OBSERVATIONS TO GUIDE COASTAL MODEL DEVELOPMENT AND ASSESSMENT

Coupling models are a commonly used path when addressing the complex interactions between different components of the Earth System, but its assessment is challenging. One such example is illustrated by Staneva et al. (2016a,b, 2017) with a focus on the nonlinear feedback between strong tidal currents and wind-waves, which can no longer be ignored, in particular in the coastal zone where its role seems to be dominant. The inclusion of wave coupling appears to decrease strong winds through wave-dependent surface roughness (Wahle et al., 2017), and changes sea surface temperature, mixing and ocean circulation (Alari et al., 2016), leading to better agreement with *in situ* and satellite measurements. Comparisons with available atmospheric and oceanic observations also show that the use of the coupled system reduces the prediction errors in the coastal ocean especially under severe storm conditions.

Significant progress has occurred in operational model skill assessment in recent years (e.g., Hernandez et al., 2015). Sotillo et al. (2016) and Pascual et al. (2017) demonstrate the utility of using Lagrangian and multiplatform observations from a single extensive campaign to assess regional and coastal high-resolution models in the Alboran Sea. However, many coastal areas remain under-validated due to the shortage of observations. This affects variables such as surface currents, highly demanded by end-users for a widespread number of applications, while observational sources for currents are generally scarce and limited to High-Frequency (HF) radar-covered areas and some mooring stations. Wherever available, HF radars have been shown to be very beneficial for validating high-resolution regional ocean models (Oke et al., 2002; Liu et al., 2009; Wilkin and Hunter, 2013; Lorente et al., 2016a,b; Soto-Navarro et al., 2016; Mourre et al., 2018; Rodrigues, unpublished, 2015). In addition, reliable wave parameters can be inferred from the weaker second-order Doppler spectrum measured by the HF radar (Lorente et al., 2018).

To improve predictions in coastal regions, it is desirable to reduce biases in the models. However, the lack of both sub-surface observations and flux data in coastal regions severely hinders progress. An example of this problem is given by the shelf-seas model around the United Kingdom. Graham et al. (2018) demonstrated that increasing the horizontal resolution from 7 to 1.5 km led to improvements in off-shelf regions, but biases remained largely unchanged over the shelf region. In the North Sea, biases in both surface and bottom temperatures (**Figures 1A,B**) suggest that stratification errors are linked either to errors in surface forcing or to vertical processes. Experiments with vertical mixing schemes (Luneva et al., 2019) and light attenuation schemes (**Figures 1C,D**) suggest that changing these would reduce biases in bottom temperatures. However, there are no flux moorings in the North Sea to evaluate the surface forcing and very few (and infrequent) subsurface observations (**Figure 1E**) to evaluate the full depth seasonal cycle.

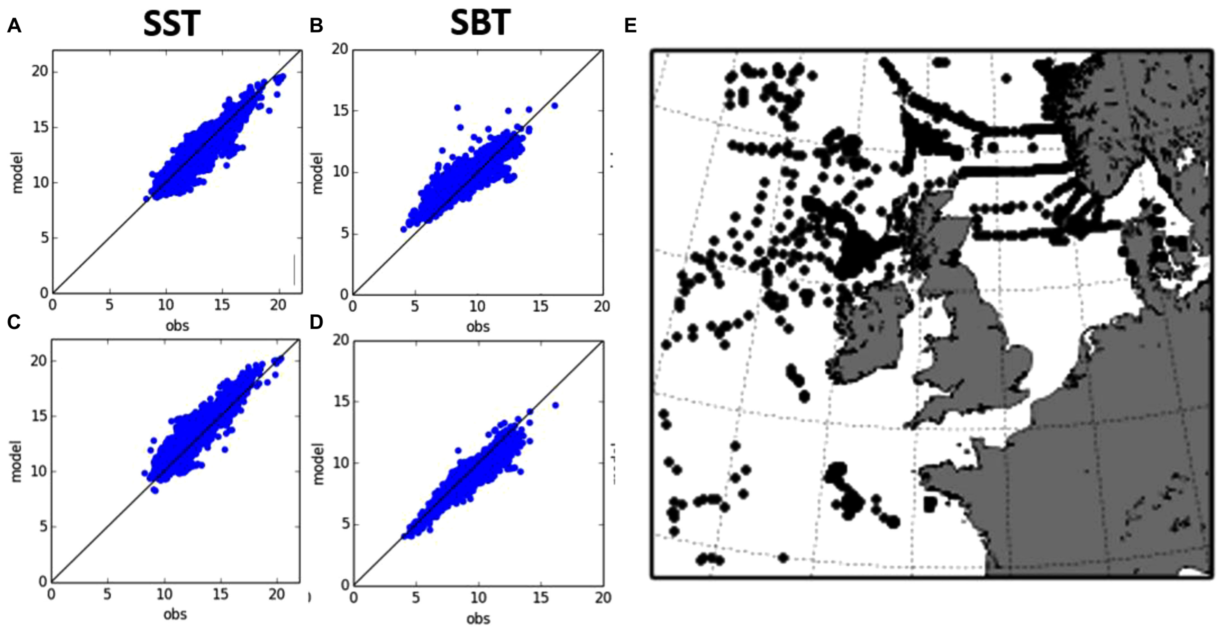

FIGURE 1 | Observed vs. modeled sea surface **(A)** and sea bottom temperature **(B)** from profile observations for the current configuration of the Met Office AMM15 shelf seas forecasting system and with proposed changes to the vertical mixing and light attenuation schemes **(C,D)**. Also shown **(E)** is a map of the location of all temperature profiles for spring 2014 available from EN4.

How valid are direct model-data comparisons? Small spatial scales and HF motions are a major challenge when comparing high-resolution model outputs to observations. Even when a model is deemed realistic, small phase errors can happen, with large consequences if strong gradients (e.g., fronts) are present. High-sampling rate time series are very valuable observations for model assessment or DA, but their representativeness when compared to model outputs remains questionable. This issue has been raised for coastal model assessment (e.g., Sandvik et al., 2016) and methods to overcome such a problem have been developed (e.g., "fuzzy" verification; Ebert, 2008). This may also call for specific strategies for the design of coastal observing networks.

USING MODELS TO CONNECT AND INTERPRET SPARSE COASTAL OBSERVATIONS

COFS must address the full spectrum of spatial and temporal scales in the coastal continuum. COFS must thus resolve interactions between nearshore, estuarine and shelf processes (target resolution: 10–100 m) and open ocean processes (target resolution: 1 km), preferably in a two-way mode. Approaches include downscaling and multi-nesting (e.g., Debreu et al., 2012; Kourafalou et al., 2015b; Trotta et al., 2017), upscaling (Schulz-Stellenfleth and Stanev, 2016), and unstructured-grid models (e.g., Zhang et al., 2016a,b; Federico et al., 2017; Stanev et al., 2017; Ferrarin et al., 2018; Maicu et al., 2018), and coupling with watersheds (Campuzano et al., 2016, 2018). These features make those COFS more relevant to the interpolation and interpretation of sparse observations.

An example is given in **Figure 2**, off the northern coast of Cuba, an area of scarce availability in ocean data and the site of an eddy field which was found to play an important role on the broader regional mesoscale processes in the Gulf of Mexico. Kourafalou et al. (2017) describe the related processes using a high-resolution nested model (Kourafalou and Kang, 2012), satellite and *in situ* data. A series of cyclonic and anticyclonic eddies were identified along the Cuban coast in the Straits of Florida and were traced in model and observational data fields. The anticyclonic eddies were released from the Loop Current and progressed eastward, affecting the overall variability of the Loop Current/Florida Current system, a component of the Gulf Stream. The synthesis of model and observational data has led to a new understanding of the Gulf of Mexico's mesoscale processes, with implications on the predictability of a major western boundary current.

The SAMOA Initiative (Alvarez Fanjul et al., 2018) uses such a synthesis of observation and model products to provide operational products and customized services for port operations in Spain. A suite of increasing-resolution models (down to ~100 m), involving wave modeling and improved metocean products, as well as dedicated observational field campaigns and near-real-time networks, is used to downscale CMEMS[1] products to coastal and port waters, providing enhanced products to end users.

[1]CMEMS: Copernicus Marine Environment Monitoring Service, http://marine.copernicus.eu/.

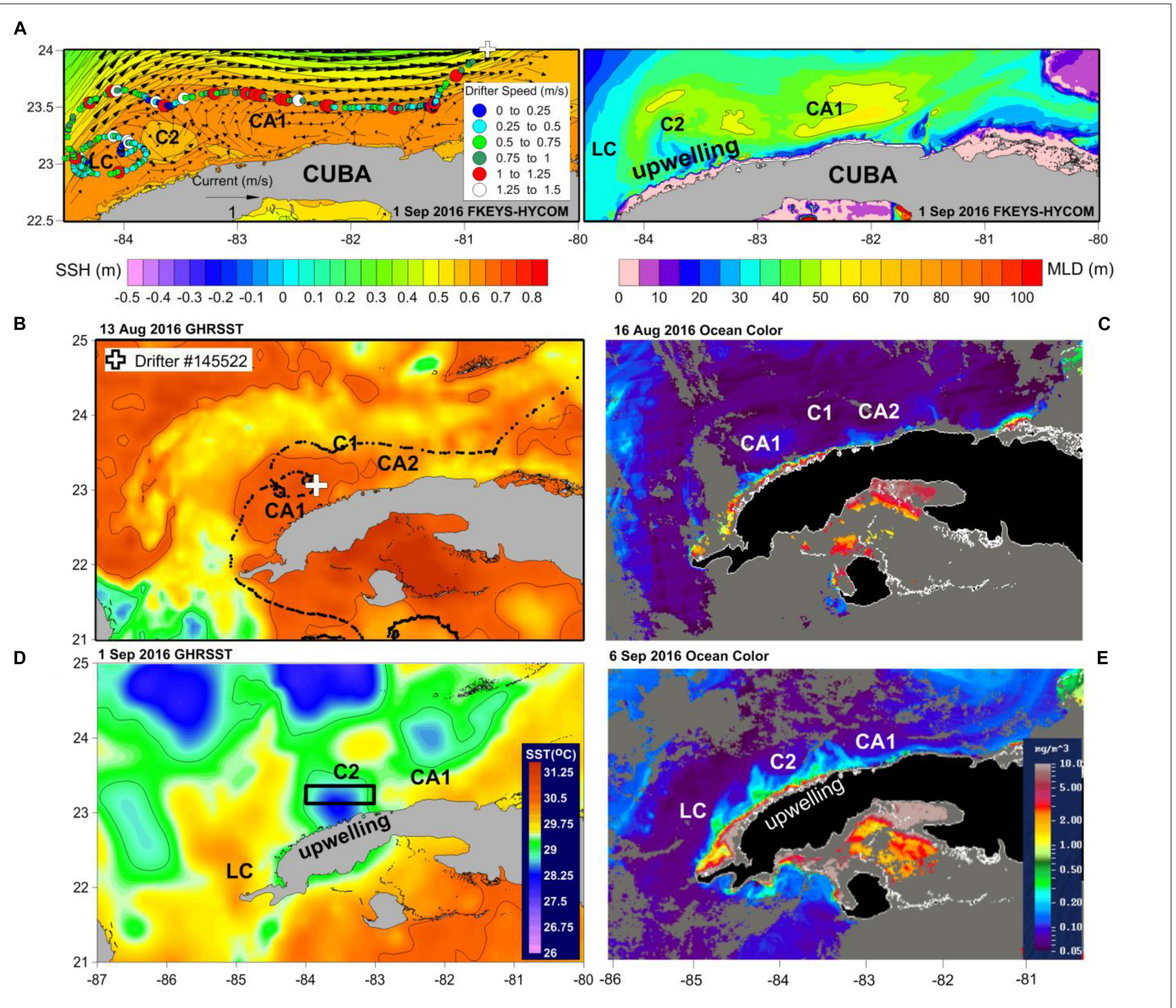

FIGURE 2 | Horizontal distribution of **(A)** Sea Surface Height (SSH) and near-surface currents and Mixed Layer Depth (MLD) derived from the FKEYS-HYCOM 1/1000 model simulation on September 1, 2016. Horizontal distribution of satellite observations: **(B)** SST (GHRSST) and **(C)** satellite ocean color in mid-August 2016 (middle panels) and the respective **(D)** SST and **(E)** ocean color in early September 2016 (lower panels). A drifter trajectory along the Straits of Florida is marked on **(A)**, circle colors denoting drifter speed (in ms^{-1}, values in the box insert); speeds over 1 ms^{-1} (red and white) are marked by larger circles; white cross symbols in panels **(A)** and **(B)** indicate the drifter's position on the particular date. The loop current (LC), the cyclonic eddies C1, C2, the anticyclonic eddies CA1, CA2 and the upwelling area along the northern Cuban coast are also marked. "Upwelling" marked over the Cuba land mass indicates upwelling area near the coast (marked by cooler/blue color waters in GHRSST data and more productive/green color waters in ocean color data). We use GHRSST Level 4 SST fields produced by GHRSST daily Level 2 data Donlon et al. (2009), https://podaac.jpl.nasa.gov/dataset/JPL-L4UHfnd-GLOB-MUR, with horizontal resolution of 1–2 km (adapted from Kourafalou et al., 2017).

USING COASTAL MODELS TO SYNTHESIZE OBSERVATIONS

Let us now turn to DA and ML approaches where models and observations are combined. DA (e.g., Moore and Martin, 2019) is traditionally complex and frustrating in coastal regions because of the multiple scales involved, and also because the data forcing is competing with open-boundary, riverine, and atmospheric forcings (the latter a DA product), which are often imperfectly known.

The value of assimilating HF radar observations to improve the coastal ocean state estimation (Oke et al., 2002; Wilkin et al., 2005; Barth et al., 2008; Shulman and Paduan, 2009; Stanev et al., 2015, 2016) or optimize boundary or surface forcings (Barth et al., 2011) has been demonstrated. Access to original radial radar measurements is important for assimilation (above references; Kurapov et al., 2003; Sperrevik et al., 2015). Reliable error variances and information on the spatially and temporally correlated error structure are very valuable (Vandenbulcke et al., 2016), but are unfortunately often unavailable.

Altimetry observations have recently been assimilated in shelf-sea systems, including operational systems (e.g., Sotillo et al., 2015; King et al., 2018). Although at an early stage compared with altimetry assimilation in global non-tidal models, use of these observations has the potential to better constrain the coastal mesoscale and the subsurface density structure. However, to derive the maximum benefit from these measurements, sub-surface temperature and salinity fields must already be reasonably well-constrained. The sparseness of profile observations in the shelf seas therefore adds to the challenge. With the upcoming launch of the SWOT wide-swath altimeter mission there will be a step-change in our ability to resolve the ocean mesoscale, but again challenges remain in making use of these low-temporal resolution observations, especially in dynamic shelf regions (cf. Gaultier et al., 2016; Bonaduce et al., 2018). For both nadir altimetry (e.g., Dibarboure et al., 2014) and future wide-swath missions, the complex budget of correlated errors at small scales ($<\sim$30 km) is certainly the main difficulty to overcome.

High-frequency measurements are found to be complementary to altimetry (Pascual et al., 2015); together they provide a strong dynamical control for ocean models (Yu et al., 2012). Other studies also assimilate SST in addition to altimetry (e.g., Vervatis et al., 2016).

Ocean-color is affected by terrestrial organic matter and sediments in case II coastal waters, besides by phytoplankton pigments (IOCCG, 2000). The increased uncertainty of chlorophyll products needs to be accounted in assimilative shelf-sea ecosystem models (Ciavatta et al., 2016) or assimilation of alternative remotely sensed optical data could be considered to constrain biogeochemical simulations, e.g., light attenuation coefficients (Ciavatta et al., 2014) and remote sensing reflectance (Jones et al., 2016).

An important research area where observations and forecasts can be better integrated is related to the development of ML techniques. For instance, Chapman and Charantonis (2017) using iterative self-organizing maps managed to reconstruct the deep ocean currents of the Southern Ocean based on surface information provided by satellites. The algorithm was trained using satellite observations of surface velocity, sea-surface height and sea-surface temperature, as well as observations of the deep current velocity from autonomous Argo floats. ML techniques can also be used in conjunction with numerical models to improve the forecasts. For instance, Kalinic et al. (2017) presented an ocean forecasting system for ocean surface currents for the northern Adriatic coastal area based on self-organizing maps trained by a high-resolution numerical weather prediction model and HF radar data. O'Donncha et al. (2018) in a case-study site in Monterey Bay (California) integrated physics-based models to resolve wave conditions together with a ML algorithm that combines forecasts from multiple, independent models into a single "best-estimate" prediction of the true state. In another example, Wahle et al. (2015) applied a novel approach of DA based on Neural Networks to wave modeling in the German Bight; French et al. (2017) combined artificial neural network with computational hydrodynamics for tidal surge inundation at estuarine ports in the United Kingdom to show that a short-term forecast of extreme water levels can achieve an accuracy that is comparable or better than the United Kingdom national tidal surge model.

USING MODELS TO DESIGN AND OPTIMIZE COASTAL OBSERVING SYSTEMS

Validated models can contribute to the efficient design and optimization of observing systems for science and operational uses (e.g., Fujii et al., 2019). Approaches include Observing System Simulation Experiments (OSSE), Observing System Experiments (OSE), and Objective Array Design (OAD) are able to handle heterogeneous, multi-platform observing systems: satellite-based, HF radars, buoys with low-cost sensors, autonomous vehicles, etc., OSSE and OSE need an assimilative system, while OAD does not (e.g., Le Hénaff et al., 2009; Charria et al., 2016; Lamouroux et al., 2016). Such approaches can be adopted in coastal regions to identify gaps in an existing observing network, to study operational failure scenarios, and to assess the potential of future observation types.

OSSE have been conducted in the last decade in the regional ocean (e.g., Halliwell et al., 2014, Halliwell et al., 2015; Aydoğdu et al., 2018). One particular challenge is to develop a rigorous OSSE approach for the interaction of open-sea and coastal scales (with particular focus on coastal scales where observations are sparser and scales shorter) adopting multi-scale models as Nature Runs to back up synthetic observations (e.g., Oke et al., 2015; Fujii et al., 2019).

Using an OSE-type approach, Pein et al. (2016) investigated how salinity measurements in the Ems Estuary affect the reconstruction of the salinity field. Indeed, estuarine and strait dynamics (Stanev et al., 2018), largely dominated by tides and their interaction with buoyancy forcing, provide a new challenge to amalgamating observations and modeling. The approach helped to identify observation locations which are more suitable for model-data synthesis.

Based on existing observing technologies, the use of autonomous platforms (e.g., gliders) or systems deployed on ships of opportunity [e.g., FerryBox, Fishery Observing Systems (FOS)] is worth investigating. The impact of those solutions, identified in previous strategy plans (Morin et al., 2015), has been illustrated in several OSSE, OSE or OAD experiments. It has been shown that assimilating glider observations (hydrology but also velocity) in ocean models does improve modeling systems (e.g., Dobricic et al., 2010; Pan et al., 2011; Jones et al., 2012; Melet et al., 2012; Hernandez-Lasheras and Mourre, 2018). Deploying gliders in coordinated network configurations will further enhance the capacity of the modeling system to reproduce targeted dynamical features (Alvarez and Mourre, 2014). Moreover, long-term repeated glider missions along endurance lines were shown to provide a new view of the ocean variability in narrow channels (Heslop et al., 2012) and in the transition zone between coastal and the open ocean (Rudnick et al., 2017). The HF sampling of surface coastal waters by FerryBox systems also delivers observations that improve assimilated model simulations (Korres et al., 2014; Stanev et al., 2016; Aydoğdu et al., 2018). Particularly, in waters where the ocean dynamics are tidally driven, the assimilating FerryBox will be more efficient than slower glider platforms (Charria et al., 2016). To fill gaps between glider tracks and FerryBox commercial lines, FOS appear as a valuable add-on to sample the water column and potentially improve operational predictions (Lamouroux et al., 2016). Aydoğdu et al. (2016) showed that those systems remain efficient even with a limited number of equipped ships if the spatial coverage is adapted to the region dynamics.

Due to the high spatial and temporal variability of the coastal patterns, the observations at the coastal scale may be deployed following an adaptive and relocatable strategy (e.g., autonomous vehicles: Ramp et al., 2009; Mourre and Alvarez, 2012). The effort spent in the recent years to build relocatable model platforms (e.g., De Dominicis et al., 2014; Rowley and Mask, 2014; Trotta et al., 2016) can guide the optimization of this adaptive observing strategy. A recently successful autonomous vessel is the Offshore Sensing SailBuoy[2], which was used for directional wave measurements in the North Sea (Hole et al., 2016). Being 100% wind propelled, the SailBuoy has two-way communication via the Iridium network. It has been used for validation of ocean models and remote sensing observations, deployed both in the Arctic and the Gulf of Mexico (Ghani et al., 2014).

CONCLUDING REMARKS

Models can play a critical role in relation with coastal observations, at connecting sparse observations, synthesizing them, and assisting the design of observational networks. In turn, whenever available, observations can guide coastal model development for research and operational use.

To adequately represent the bidirectional interactions between the open ocean and small-scale processes, a better integration and coordination of coastal and large-scale observation systems would be beneficial. A promising combination would involve HF radars and reprocessed coastal altimetry data (Gommenginger et al., 2011).

Progress must be made in the next decade on coastal observations, in particular regarding surface currents, subsurface observations and flux data, and strategies must be developed to assess the smallest scales (plumes, fronts, plankton blooms, etc.). Likely upcoming breakthroughs will be Sentinel-3A wind, wave and optical measurements (Heslop et al., 2017; Pahlevan et al., 2017; Schulz-Stellenfleth and Staneva, 2018; Wiese et al., 2018), synthetic aperture radar (SAR)-based wide-swath altimetry (SWOT), the WaCM mission (Rodriguez et al., 2019), and the SKIM[3] mission, if approved. The availability of accurate, community-agreed bathymetry, reference levels and coastline products are also critical, since without them one cannot get HF processes right nor ensure consistency of coastal models with basin-scale models (e.g., Toublanc et al., 2018). The situation regarding freshwater fluxes and the monitoring of rivers is contrasted (Mishra and Coulibaly, 2009); neither river climatologies nor watershed models are fully satisfactory (Campuzano et al., 2016). Validated observational error estimates must also be a priority.

One of the challenges of coastal ocean observing systems in the next decades is the integration of new and conventional technologies to monitor the variability at small scales and through integration into multiplatform observing and forecasting systems (Tintoré et al., 2013). The establishment of coastal ocean observing systems is being implemented as an important component of marine strategy. These coastal observatories, such as the Integrated Marine Observing System (IMOS) in Australia, the Ocean Observing Initiative (OOI), and the Integrated Ocean Observing System (IOOS) in the United States, Neptune and Venus in Canada, the Coastal Observing System for Northern and Arctic Seas (COSYNA) Project in Germany, Poseidon in Greece, and SOCIB in Spain are today providing new quality controlled observational datasets following standard and international protocols.

New insights on coastal processes can be gained from the measurements of trace elements and isotopes. For instance, radium isotopes (Moore, 2000; Charette et al., 2016) have proven capable of tracing continental waters into the ocean from rivers, estuaries or submarine groundwater discharge.

Finally, coastal areas are ideal in engaging the public in current scientific challenges and raise their awareness on global environmental concerns of immense importance, including global warming and plastic pollution (Cigliano et al., 2015). Citizen science data collected in coastal areas have reached the quality appropriate for exploitation in marine policy (Hyder et al., 2015), coastal area monitoring (Brewin et al., 2015, 2017b) and scientific studies (e.g., for the evaluation of satellite data in coastal regions, Brewin et al., 2017a; Yang et al., 2018). Citizen science data can cover areas that are typically under-sampled by traditional monitoring networks (e.g., intertidal zone) and may offer new opportunities for a quantitative evaluation or assimilation into coastal models. Citizen feedback can even be useful in guiding future observation strategies and model development. Engaging citizens can improve ocean literacy, providing support for future coastal monitoring and modeling (Garcia-Soto et al., 2017). The delivery of sector-focused operational products and services (e.g., Heslop et al., 2019) will progressively allow exploiting and help in developing the full potential of our present

[2]www.sailbuoy.no

[3]https://www.skim-ee9.org/

coastal ocean observing and forecasting capabilities. This will allow in turn receiving the necessary feedback from the user communities to guide future observation and evolution strategies.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

REFERENCES

Alari, V., Staneva, J., Breivik, O., Bidlot, J. R., Mogensen, K., and Janssen, P. A. E. M. (2016). Response of water temperature to surface wave effects in the Baltic Sea: simulations with the coupled NEMO-WAM model. *Ocean Dyn.* 66:917. doi: 10.1007/s10236-016-0963-x

Alvarez, A., and Mourre, B. (2014). Cooperation or coordination of underwater glider networks? An assessment from observing system simulation experiments in the Ligurian Sea. *J. Atmos. Oceanic Technol.* 31, 2268–2277. doi: 10.1175/jtech-d-13-00214.1

Alvarez Fanjul, E., Marcos, G., Gómez, B. P., Valdecasas's, J. G., Rubio's, S. P., Lorente, P., et al. (2018). "Operational oceanography at the service of the ports," in *New Frontiers in Operational Oceanography*, eds E. Chassignet, A. Pascual, J. Tintoré, and J. Verron (GODAE: OceanView), 729–736. doi: 10.17125/gov2018.ch27.729

Aydoğdu, A., Hoar, T. J., Vukicevic, T., Anderson, J. L., Pinardi, N., Karspeck, A., et al. (2018). OSSE for a sustainable marine observing network in the Sea of Marmara, Nonlin. *Process. Geophys.* 25, 537–551. doi: 10.5194/npg-25-537-2018

Aydoğdu, A., Pinardi, N., Pistoia, J., Martinelli, M., Belardinelli, A., and Sparnocchia, S. (2016). Assimilation experiments for the fishery observing system in the Adriatic Sea. *J. Mar. Syst.* 162, 126–136. doi: 10.1016/j.jmarsys.2016.03.002

Barth, A., Alvera-Azcárate, A., Beckers, J. M., Staneva, J., Stanev, E. V., and Schulz-Stellenfleth, J. (2011). Correcting surface winds by assimilating high-frequency radar surface currents in the German Bight. *Ocean Dyn.* 61, 599–610. doi: 10.1007/s10236-010-0369-0

Barth, A., Alvera-Azcárate, A., and Weisberg, R. H. (2008). Assimilation of high-frequency radar currents in a nested model of the West Florida Shelf. *J. Geophys. Res.* 113:C08033. doi: 10.1029/2007JC004585

Bonaduce, A., Benkiran, M., Remy, E., Le Traon, P. Y., and Garric, G. (2018). Contribution of future wide swath altimetry missions to ocean analysis and forecasting. *Ocean Sci. Discuss.* 14, 1405–1421. doi: 10.5194/os-2018-58

Brewin, R. J. W., de Mora, L., Jackson, T., Brewin, T. G., and Shutler, J. (2015). On the potential of surfers to monitor environmental indicators in the coastal zone. *PLoS One* 10:e0127706. doi: 10.1371/journal.pone.0127706

Brewin, R. J. W., de Mora, L., Billson, O., Jackson, T., Russell, P., Brewin, T. G., et al. (2017a). Evaluating operational AVHRR sea surface temperature data at the coastline using surfers. *Estuar. Coast. Shelf Sci.* 196, 276–289. doi: 10.1016/j.ecss.2017.07.011

Brewin, R. J. W., Hyder, K., Andersson, A. J., Billson, O., Bresnahan, P. J., Brewin, T. G., et al. (2017b). Expanding aquatic observations through recreation. *Front. Mar. Sci.* 4:351. doi: 10.3389/fmars.2017.00351

Campuzano, F., Brito, D., Juliano, M., Fernandes, R., de Pablo, H., and Neves, R. (2016). Coupling watersheds, estuaries, and regional ocean through numerical modelling for Western Iberia: a novel methodology. *Ocean Dyn.* 66, 1745–1756. doi: 10.1007/s10236-016-1005-4

Campuzano, F. J., Juliano, M., Sobrinho, J., de Pablo, H., Brito, D., Fernandes, R., et al. (2018). in *Coupling Watersheds, Estuaries and Regional Oceanography through Numerical Modelling in the Western Iberia: Thermohaline Flux Variability at the Ocean-Estuary Interface*, ed. E. W. Froneman (Rijeka: IntechOpen). doi: 10.5772/intechopen.72162

Chapman, C., and Charantonis, A. (2017). Reconstruction of subsurface velocities from satellite observations using iterative self-organizing maps. *IEEE Geosci. Remote Sens. Lett.* 14, 617–620. doi: 10.1109/lgrs.2017.2665603

Charette, M. A., Lam, P. J., Lohan, M. C., Kwon, E. Y., Hatje, V., Jeandel, C., et al. (2016). Coastal ocean and shelf-sea biogeochemical cycling of trace elements and isotopes: lessons learned from GEOTRACES. *Philos. Trans. R. Soc. A* 374:20160076. doi: 10.1098/rsta.2016.0076

Charria, G., Lamouroux, J., and De Mey, P. (2016). Optimizing observation networks combining gliders, moored buoys and FerryBox in the Bay of Biscay and english channel. *J. Mar. Syst.* 162, 112–125. doi: 10.1016/j.jmarsys.2016.04.003

Ciavatta, S., Kay, S., Saux-Picart, S., Butenschön, M., and Allen, J. I. (2016). Decadal reanalysis of biogeochemical indicators and fluxes in the North West European shelf-sea ecosystem. *J. Geophys. Res. Oceans* 121, 1824–1845. doi: 10.1002/2015jc011496

Ciavatta, S., Torres, R., Martinez-Vicente, V., Smyth, T., Dall'Olmo, G., Polimene, L., et al. (2014). Assimilation of remotely-sensed optical properties to improve marine biogeochemistry modelling. *Prog. Oceanogr.* 127, 74–95. doi: 10.1016/j.pocean.2014.06.002

Cigliano, J. A., Meyer, R., Ballard, H. L., Freitag, A., Phillips, T. B., and Wasser, A. (2015). Making marine and coastal citizen science matter. *Ocean Coast. Manag.* 115, 77–87. doi: 10.1016/j.ocecoaman.2015.06.012

Davidson, F., Chassignet, E., Vinayachandran, P. N., Lu, Y., Smith, G. C., Zhu, X., et al. (2019). Synergies in operational oceanography: the intrinsic need for sustained ocean observations. *Front. Mar. Sci.* (in press). doi: 10.3389/fmars.2019.00450

De Dominicis, M., Falchetti, S., Trotta, F., Pinardi, N., Giacomelli, L., Napolitano, E., et al. (2014). A relocatable ocean model in support of environmental emergencies. *Ocean Dyn.* 64, 667–688. doi: 10.1007/s10236-014-0705-x

De Mey, P., Stanev, E., and Kourafalou, V. (2017). Science in support of coastal ocean forecasting — part 1. *Ocean Dyn.* 67, 665–668. doi: 10.1007/s10236-017-1048-1

Debreu, L., Marchesiello, P., Penven, P., and Cambon, G. (2012). Two-way nesting in split-explicit ocean models: algorithms, implementation and validation. *Ocean Mode.* 49–50, 1–21. doi: 10.1016/j.ocemod.2012.03.003

Dibarboure, G., Boy, F., Desjonqueres, J. D., Labroue, S., Lasne, Y., Picot, N., et al. (2014). Investigating short-wavelength correlated errors on low-resolution mode altimetry. *J. Atmos. Oceanic Technol.* 31, 1337–1362. doi: 10.1175/JTECH-D-13-00081.1

Dobricic, S., Pinardi, N., Testor, P., and Send, U. (2010). Impact of data assimilation of glider observations in the Ionian Sea (Eastern Mediterranean). *Dyn. Atmos. Oceans* 50, 78–92. doi: 10.1016/j.dynatmoce.2010.01.001

Donlon, C. J., Casey, K. S., Robinson, I. S., Gentemann, C. L., Reynolds, R. W., Barton, I., et al. (2009). The GODAE high-resolution sea surface temperature pilot project. *Oceanography* 22, 34–45. doi: 10.5670/oceanog.2009.64

Ebert, E. (2008). Fuzzy verification of high-resolution gridded forecasts: a review and proposed framework. *Meteorol. Appl.* 15, 51–64. doi: 10.1002/met.25

Federico, I., Pinardi, N., Coppini, G., Oddo, P., Lecci, R., and Mossa, M. (2017). Coastal ocean forecasting with an unstructured grid model in the southern Adriatic and northern Ionian seas. *Nat. Hazards Earth Syst. Sci.* 17, 45–59. doi: 10.1016/j.marpolbul.2014.10.039

Ferrarin, C., Bellafiore, D., Sannino, G., Bajo, M., and Umgiesser, G. (2018). Tidal dynamics in the inter-connected Mediterranean, Marmara, Black and Azov seas. *Prog. Oceanogr.* 161, 102–115. doi:10.1016/j.pocean.2018.02.006

French, J., Mawdsley, E., Fujiyama, T., and Achuthan, K. (2017). Combining machine learning with computational hydrodynamics for prediction of tidal surge inundation at estuarine ports. *Proc. IUTAM* 25, 28–35. doi: 10.1016/j.piutam.2017.09.005

Fujii, Y., Zuo, H., Oke, P. R., Halliwell, G. R., Gasparin, F., Loose, N., et al. (2019). Observing system evaluation based on ocean data assimilation and prediction systems: on-going challenges and future vision for designing/supporting ocean observational networks. *Front. Mar. Sci.* (in press). doi: 10.3389/fmars.2019.00417

Garcia-Soto, C., van der Meeren, G. I., Busch, J. A., Delany, J., Domegan, C., Dubsky, K., et al. (2017). "Advancing citizen science for coastal and ocean research. technical report," in *Position Paper 23 of the European Marine Board*, eds V. French, P. Kellett, J. Delany, and N. McDonough (Ostend).

Gaultier, L., Ubelmann, C., and Fu, L.-L. (2016). The challenge of using future SWOT data for oceanic field reconstruction. *J. Atmos. Oceanic Technol.* 33:119. doi: 10.1175/JTECH-D-15-0160.1

Ghani, M. H., Hole, L. R., Fer, I., Kourafalou, V. H., Wienders, N., Kang, H., et al. (2014). The SailBuoy remotely-controlled unmanned vessel: measurements of near surface temperature, salinity and oxygen concentration in the Northern Gulf of Mexico. *Methods Oceanogr.* 10, 104–121. doi: 10.1016/j.mio.2014.08.001

Gommenginger, C., Thibaut, P., Fenoglio-Marc, L., Quartly, G., Deng, X., Gómez-Enri, J., et al. (2011). "Retracking altimeter waveforms near the coasts," in *Coastal Altimetry*, eds S. Vignudelli, A. Kostianoy, P. Cipollini, and J. Benveniste (Berlin: Springer).

Graham, J. A., O'Dea, E., Holt, J., Polton, J., Hewitt, H. T., Furner, R., et al. (2018). AMM15: a new high-resolution NEMO configuration for operational simulation of the European north-west shelf. *Geosci. Model. Dev.* 11, 681–696. doi: 10.5194/gmd-11-681-2018

Halliwell, G. R. Jr., Kourafalou, V. H., Le Hénaff, M., Shay, L., and Atlas, R. (2015). OSSE impact analysis of airborne ocean surveys for improving upper-ocean dynamical and thermodynamical forecasts in the Gulf of Mexico. *Prog. Oceanogr.* 130, 32–46. doi: 10.1016/j.pocean.2014.09.004

Halliwell, G. R., Srinivasan, A., Kourafalou, V. H., Yang, H., Willey, D., Le Hénaff, M., et al. (2014). Rigorous evaluation of a fraternal twin ocean OSSE system for the open Gulf of Mexico. *J. Atmos. Ocean. Techn.* 31, 105–130. doi: 10.1175/JTECH-D-13-00011.1

Hernandez, F., Blockley, E., Brassington, G. B., Davidson, F., Divakaran, P., Drévillon, M., et al. (2015). Recent progress in performance evaluations and near real-time assessment of operational ocean products. *J. Operat. Oceanogr.* 8, 221–238.

Hernandez-Lasheras, J., and Mourre, B. (2018). Dense CTD survey versus glider fleet sampling: comparing data assimilation performance in a regional ocean model west of Sardinia. *Ocean Sci.* 14, 1069–1084. doi: 10.5194/os-14-1069-2018

Heslop, E., Ruiz, S., Allen, J., Lopez-Jurado, J., Renault, L., and Tintoré, J. (2012). Autonomous underwater gliders monitoring variability at "choke points" in our ocean system: a case study in the Western Mediterranean Sea. *Geophys. Res. Lett.* 39:L20604.

Heslop, E., Tintoré, J., Rotllan, P., Álvarez-Berastegui, D., Fontera, B., Mourre, B., et al. (2019). SOCIB integrated multi-platform ocean observing and forecasting: from ocean data to sector-focused delivery of products and services. *J. Operat. Oceanogr.* (in press). doi: 10.1080/1755876X.2019.1582129

Heslop, E. E., Saìnchez-Romaìn, A., Pascual, A., Rodriìguez, D., Reeve, K. A., FaugeÌre, Y., et al. (2017). Sentinel-3A views ocean variability more accurately at finer resolution. *Geophys. Res. Lett.* 44, 367–312. doi: 10.1002/2017GL076244

Hole, L. R., Fer, I., and Peddie, D. (2016). Directional wave measurements using an autonomous vessel. *Ocean Dyn.* 66, 1087–1098. doi: 10.1007/s10236-016-0969-4

Hyder, K., Townhill, B., Anderson, L. G., Delany, J., and Pinnegar, J. K. (2015). Can citizen science contribute to the evidence-base that underpins marine policy? *Mar. Policy* 59, 112–120. doi: 10.1016/j.marpol.2015.04.022

IOCCG (2000). "Remote sensing of ocean colour in coastal, and other optically-complex, waters," in *Reports of the International Ocean-Colour Coordinating Group, No. 3*, ed. S. Sathyendranath (Dartmouth: IOCCG).

Jones, E. M., Baird, M. E., Mongin, M., Parslow, J., Skerratt, J., Lovell, J., et al. (2016). Use of remote-sensing reflectance to constrain a data assimilating marine biogeochemical model of the Great Barrier Reef. *Biogeosciences* 13, 6441–6469. doi: 10.5194/bg-13-6441-2016

Jones, E. M., Oke, P., Rizwi, F., and Murray, L. M. (2012). Assimilation of glider and mooring data into a coastal ocean model. *Ocean Model.* 47, 1–13. doi: 10.1016/j.ocemod.2011.12.009

Kalinic, H., Mihanovic, H., Cosoli, S., Tudor, M., and Vilibic, I. (2017). Predicting ocean surface currents using numerical weather prediction model and Kohonen neural network: a northern Adriatic study. *Neural Comput. Appl.* 28(Suppl.1), S611–S620.

King, R. R., While, J., Martin, M. J., Lea, D. J., Lemieux-Dudon, B., Waters, J., et al. (2018). Improving the initialisation of the Met Office operational shelf-seas model. *Ocean Model.* 130:1. doi: 10.1016/j.ocemod.2018.07.004

Korres, G., Ntoumas, M., Potiris, M., and Petihakis, G. (2014). Assimilating ferry box data into the Aegean Sea model. *J. Mar. Syst.* 140-A, 59–72. doi: 10.1016/j.jmarsys.2014.03.013

Kourafalou, V. H., Androulidakis, Y. S., Kang, H., and Le Hénaff, M. (2017). The dynamics of Cuba anticyclones (CubANs) and interaction with the Loop Current / Florida Current system. *J. Geophys. Res.* 122, 7897–7923. doi: 10.1002/2017JC012928

Kourafalou, V. H., De Mey, P., Le Henaff, M., Charria, G., Edwards, C. A., He, R., et al. (2015a). Coastal Ocean Forecasting: system integration and evaluation. *J. Operat. Oceanogr.* 8, S127–S146. doi: 10.1080/1755876X.2015.1022336

Kourafalou, V. H., De Mey, P., Staneva, J., Ayoub, N., Barth, A., Chao, Y., et al. (2015b). Coastal ocean forecasting: science foundation and user benefits. *J. Operat. Oceanogr.* 8, 147–167.

Kourafalou, V. H., and Kang, H. (2012). Florida Current meandering and evolution of cyclonic eddies along the Florida Keys Reef Tract: are they inter-connected? *J. Geophys. Res.* 117:C05028. doi: 10.1029/2011JC007383

Kurapov, A. L., Egbert, G. D., Allen, J. S., Miller, R. N., Erofeeva, S. Y., and Kosro, P. (2003). The M_2 internal tide off Oregon: inferences from data assimilation. *J. Phys. Oceanogr.* 33, 1733–1757. doi: 10.1175/2397.1

Lamouroux, J., Charria, G., De Mey, P., Raynaud, S., Heyraud, C., Craneguy, P., et al. (2016). Objective assessment of the contribution of the RECOPESCA network to the monitoring of 3D coastal ocean variables in the Bay of Biscay and the English Channel. *Ocean Dyn.* 66, 567–588. doi: 10.1007/s10236-016-0938-y

Le Hénaff, M., De Meyet, P., and Marsaleix, P. (2009). "Assessment of observational networks with the representer matrix spectra method – application to a 3-D coastal model of the Bay of Biscay," in *Proceedings of the Workshop on Special Issue of Ocean Dynamics, 2007 GODAE Coastal and Shelf Seas*, Vol. 59, (Liverpool), 3–20. doi: 10.1007/s10236-008-0144-7

Liu, Y., MacCready, P., Hickey, B. M., Dever, E. P., Kosro, P. M., and Banas, N. S. (2009). Evaluation of a coastal ocean circulation model for the Columbia River plume in summer 2004. *J. Geophys. Res.* 114:C00B04. doi: 10.1029/2008JC004929

Lorente, P., Piedracoba, S., Sotillo, M. G., Aznar, R., Amo-Baladrón, A., Pascual, A., et al. (2016a). Characterizing the surface circulation in Ebro Delta (NW Mediterranean) with HF radar and modeled current data. *J. Mar. Syst.* 163, 61–79. doi: 10.1016/j.jmarsys.2016.07.001

Lorente, P., Piedracoba, S., Sotillo, M. G., Aznar, R., Amo-Baladrón, A., Pascual, A., et al. (2016b). Ocean model skill assessment in the NW Mediterranean using multi-sensor data. *J. Operat. Oceanogr.* 9, 75–92. doi: 10.1080/1755876X.2016.1215224

Lorente, P., Sotillo, M. G., Aouf, L., Amo-Baladrón, A., Barrera, E., Dalphinet, A., et al. (2018). Extreme wave height events in NW Spain: a combined multi-sensor and model approach. *Remote Sens.* 10:1. doi: 10.3390/rs10010001

Luneva, M. V., Wakelin, S., Holt, J. T., Inall, M. E., Kozlov, I. E., Palmer, M. R., et al. (2019). Challenging vertical turbulence mixing schemes in a tidally energetic environment: Part I. 3D shelf-sea model assessment. *J. Geophys. Res. Oceans* (in press). doi: 10.1029/2018JC014307

Maicu, F., De Pascalis, F., Ferrarin, C., and Umgiesser, G. (2018). Hydrodynamics of the Po River-Delta-Sea system. *J. Phys. Res. Oceans* 123, 6349–6372. doi: 10.1029/2017JC013601

Melet, A., Verron, J., and Brankart, J.-M. (2012). Potential outcomes of glider data assimilation in the Solomon Sea: control of the water mass properties and parameter estimation. *J. Mar. Syst.* 94, 232–246. doi: 10.1016/j.jmarsys.2011.12.003

Mishra, A. K., and Coulibaly, P. (2009). Developments in hydrometric network design: a review. *Rev. Geophys.* 47:RG2001.

Moore, A. M., and Martin, M. J. (2019). Synthesis of ocean observations using data assimilation: toward a more complete picture of the State of the Ocean. *Front. Mar. Sci.* 6:90. doi: 10.3389/fmars.2019.00090

Moore, W. S. (2000). Determining coastal mixing rates using radium isotopes. *Cont. Shelf Res.* 20, 1993–2007. doi: 10.1016/s0278-4343(00)00054-6

Morin, P., Krieger, M., Durand, D., Puillat, I., and Farcy, P. (2015). *The Joint European Research Infrastructure Network for Coastal Observatories: Achievements and Strategy for the Future.* Available at: http://archimer.ifremer.fr/doc/00349/46022/ (accessed November 28, 2015).

Mourre, B., Aguiar, E., Juza, M., Hernandez-Lasheras, J., Reyes, E., Heslop, E., et al. (2018). "Assessment of high-resolution regional ocean prediction systems using multi-platform observations: illustrations in the Western Mediterranean Sea," in *New Frontiers in Operational Oceanography*, eds E. Chassignet, A. Pascual, J. Tintoré, and J. Verron (GODAE: OceanView), 663–694. doi: 10.17125/gov2018.ch24

Mourre, B., and Alvarez, A. (2012). Benefit assessment of glider adaptive sampling in the Ligurian Sea. *Deep Sea Res. I* 68, 68–72.

O'Donncha, F., Zhang, Y., Chen, B., and James, S. C. (2018). An integrated framework that combines machine learning and numerical models to improve wave-condition forecasts. *J. Mar. Syst.* 186, 29–36. doi: 10.1016/j.jmarsys.2018.05.006

Oke, P. R., Allen, J. S., Miller, R. N., Egbert, G. D., and Kosro, P. M. (2002). Assimilation of surface velocity data into a primitive equation coastal ocean model. *J. Geophys. Res.* 107:3122. doi: 10.1029/2000JC000511

Oke, P. R., Larnicol, G., Jones, E. M., Kourafalou, V. H., Sperrevik, A. K., Carse, F., et al. (2015). Assessing the impact of observations on ocean forecasts and reanalyses: part 2: regional applications. *J. Oper. Oceanogr.* 8, S63–S79. doi: 10.1080/1755876X.2015.1022080

Pahlevan, N., Sarkar, S., Franz, B. A., Balasubramanian, S. V., and He, J. (2017). Sentinel-2 MultiSpectral Instrument (MSI) data processing for aquatic science applications: demonstrations and validations. *Remote Sens. Environ.* 201, 47–56. doi: 10.1016/j.rse.2017.08.033

Pan, C., Yaremchuk, M., Nechaev, D., and Ngodock, H. (2011). Variational assimilation of glider data in Monterey Bay. *J. Mar. Res.* 69, 331–346. doi: 10.1357/002224011798765259

Pascual, A., Lana, A., Troupin, C., Ruiz, S., Faugère, Y., Escudier, R., et al. (2015). Assessing SARAL/AltiKa delayed-time data in the coastal zone: comparisons with HF radar observations. *Mar. Geodesy* 8, 260–276. doi: 10.1080/01490419.2015.1019656

Pascual, A., Ruiz, S., Olita, A., Troupin, C., Claret, M., Casas, B., et al. (2017). A multiplatform experiment to Unravel Meso- and submesoscale processes in an intense front (AlborEx). *Front. Mar. Sci.* 4:39. doi: 10.3389/fmars.2017.00039

Pein, J. U., Grayek, S., Schulz-Stelleneth, J., and Stanev, E. V. (2016). On the impact of salinity observations on state estimates in Ems Estuary. *Ocean Dyn.* 66, 243–262. doi: 10.1007/s10236-015-0920-0

Ponte, R. M., Carson, M., Cirano, M., Domingues, C., Jevrejeva, S., Marcos, M., et al. (2019). Towards comprehensive observing and modeling systems for monitoring and predicting regional to coastal sea level. *Front. Mar. Sci.* (in press). doi: 10.3389/fmars.2019.00437

Ramp, S., Davis, R., Leonard, N., Shulman, I., Chao, Y., Robinson, A., et al. (2009). Preparing to predict: the second autonomous ocean sampling network (AOSN-II) experiment on the Monterey Bay. *Deep Sea Res. II* 56, 68–87.

Rodriguez, E., Bourassa, M., Chelton, D., Farrar, T., Long, D., Perkovic-Martin, D., et al. (2019). The winds and currents mission concept. *Front. Mar. Sci.* (in press). doi: 10.3389/fmars.2019.00438

Rowley, C., and Mask, A. (2014). Regional and coastal prediction with the relocatable ocean nowcast/forecast system. *Oceanography* 27, 44–55. doi: 10.5670/oceanog.2014.67

Rudnick, D., Zaba, K., Todd, R., and Davis, R. (2017). A climatology of the California current system from a network of underwater gliders. *Prog. Oceanogr.* 154, 64–106. doi: 10.1016/j.pocean.2017.03.002

Sandvik, A. D., Skagseth, Ø, and Skogen, M. D. (2016). Model validation: issues regarding comparisons of point measurements and high-resolution modeling results. *Ocean Model.* 106, 68–73. doi: 10.1016/j.ocemod.2016.09.007

Schulz-Stellenfleth, J., and Stanev, E. V. (2016). Analysis of the upscaling problem - a case study for the barotropic dynamics in the North Sea and the German Bight. *Ocean Model.* 100, 109–124. doi: 10.1016/j.ocemod.2016.02.002

Schulz-Stellenfleth, J., and Staneva, J. (2018). A multi collocation method for coastal zone observations with applications to SENTINEL-3a altimeter wave height data. *Ocean Sci.* 15, 249–268. doi: 10.5194/os-2018-124

Shulman, I., and Paduan, J. D. (2009). Assimilation of HF radar-derived radials and total currents in the Monterey Bay area. *Deep Sea Res. Part II Top. Stud. Oceanogr.* 56, 149–160. doi: 10.1016/j.dsr2.2008.08.004

Sotillo, M. G., Amo-Baladrón, A., Padorno, E., Garcia-Ladona, E., Orfila, A., Rodríguez-Rubio, P., et al. (2016). How is the surface Atlantic water inflow through the Gibraltar Strait forecasted? A lagrangian validation of operational oceanographic services in the Alboran Sea and the Western Mediterranean. *Deep Sea Res. II* 133, 100–117. doi: 10.1016/j.dsr2.2016.05.020

Sotillo, M. G., Cailleau, S., Lorente, P., Levier, B., Aznar, R., Reffray, G., et al. (2015). The MyOcean IBI ocean forecast and reanalysis systems: operational products and roadmap to the future copernicus service. *J. Oper. Oceanogr.* 8:63. doi: 10.1080/1755876X.2015.1014663

Soto-Navarro, J., Lorente, P., Fanjul, E. A., Sánchez-Garrido, J. C., and García-Lafuente, J. (2016). Surface circulation at the Strait of Gibraltar: a combined hf radars and high resolution model study. *J. Geophys. Res. Oceans* 121, 2016–2034. doi: 10.1002/2015jc011354

Sperrevik, A. K., Christensen, K. H., and Röhrs, J. (2015). Constraining energetic slope currents through assimilation of high-frequency radar observations. *Ocean Sci.* 11, 237–249. doi: 10.5194/os-11-237-2015

Stanev, E., Schulz-Stellenfleth, J., Staneva, J., Grayek, S., Grashorn, S., Behrens, A., et al. (2016). Ocean forecasting for the German Bight: from regional to coastal scales. *Ocean Sci.* 12, 1105–1136. doi: 10.5194/os-12-1105-2016

Stanev, E. V., Grashorn, S., and Zhang, Y. J. (2017). Cascading ocean basins: numerical simulations of the circulation and interbasin exchange in the Azov-Black-Marmara-Mediterranean Seas system. *Ocean Dyn.* 67, 1003–1025. doi: 10.1007/s10236-017-1071-2

Stanev, E. V., Pein, J., Grashorn, S., Zhang, Y. J., and Schrum, C. (2018). Dynamics of the Baltic Sea Straits via numerical simulation of exchange flows. *Ocean Model.* 131, 40–58. doi: 10.1016/j.ocemod.2018.08.009

Stanev, E. V., Ziemer, F., Schulz-Stellenfleth, J., Seemann, J., Staneva, J., and Gurgel, K. W. (2015). Blending surface currents from HF radar observations and numerical modelling: tidal hindcasts and forecasts. *J. Atmos. Oceanic Technol.* 32, 256–281. doi: 10.1175/jtech-d-13-00164.1

Staneva, J., Alari, V., Breivik, O., Bidlot, J.-R., and Mogensen, K. (2017). Effects of wave-induced forcing on a circulation model of the North Sea. *Ocean Dyn.* 67, 81–101. doi: 10.1007/s10236-016-1009-0

Staneva, J., Wahle, K., Günther, H., and Stanev, E. (2016a). Coupling of wave and circulation models in coastal-ocean predicting systems: a case study for the German Bight. *Ocean Sci.* 12, 797–806. doi: 10.5194/os-12-797-2016

Staneva, J., Wahle, K., Koch, W., Behrens, A., Fenoglio-Marc, L., and Stanev, E. (2016b). Coastal flooding: impact of waves on storm surge during extremes – a case study for the German Bight. *Nat. Hazards Earth Syst. Sci.* 16, 2373–2389. doi: 10.5194/nhess-16-2373-2016

Tintoré, J., Casas, B., Heslop, E., Vizoso, G., Pascual, A., Orfila, A., et al. (2013). "The impact of new multi-platform observing systems in science, technology development and response to society needs; from small to large scales," in *Computer Aided Systems Theory - EUROCAST*, Vol. 8112, eds R. Moreno-Díaz, F. Pichler, and A. Quesada-Arencibia (Berlin: Springer), 341–348.

Toublanc, F., Ayoub, N., Lyard, F., Marsaleix, P., and Allain, D. (2018). Tidal downscaling from the open ocean to the coast: a new approach applied to the Bay of Biscay. *Ocean Model.* 124, 16–32. doi: 10.1016/j.ocemod.201802001

Trotta, F., Fenu, E., Pinardi, N., Bruciaferri, D., Giacomelli, L., Federico, I., et al. (2016). A structured and unstructured grid relocatable ocean platform for forecasting (SURF). *Deep Sea Res. Part II* 133, 54–75. doi: 10.1016/j.dsr2.2016.05.004

Trotta, F., Pinardi, N., Fenu, E., Grandi, A., and Lyubartsev, V. (2017). Multinest high-resolution model of submesoscale circulation features in the Gulf of Taranto. *Ocean Dyn.* 67, 1609–1625. doi: 10.1007/s10236-017-1110-z

Vandenbulcke, L., Beckers, J. M., and Barth, A. (2016). Correction of inertial oscillations by assimilation of HF radar data in a model of the Ligurian Sea. *Ocean Dyn.* 67, 117–135. doi: 10.1007/s10236-016-1012-5

Vervatis, V., Testut, C. E., De Mey, P., Ayoub, N., Chanut, J., and Quattrocchi, G. (2016). Data assimilative twin-experiment in a high-resolution Bay of Biscay configuration: 4D EnOI based on stochastic modelling of the wind forcing. *Ocean Model.* 100, 1–19. doi: 10.1016/j.ocemod.2016.01.003

Wahle, K., Staneva, J., and Günther, H. (2015). Data assimilation of ocean wind waves using neural networks. A case study for the German Bight. *Ocean Model.* 96, 117–125. doi: 10.1016/j.ocemod.2015.07.007

Wahle, K., Staneva, J., Koch, W., Fenoglio-Marc, L., Ho-Hagemann, H., and Stanev, E. (2017). An atmosphere-wave regional coupled model: improving predictions of wave heights and surface winds in the Southern North Sea. *Ocean Sci.* 13, 289–301. doi: 10.5194/os-13-289-2017

Wiese, A., Staneva, J., Schultz-Stellenfleth, J., Behrens, A., Fenoglio-Marc, L., and Bidlot, J. (2018). Synergy between satellite observations and model simulations during extreme events. *Ocean Sci.* 14, 1503–1521. doi: 10.5194/os-2018-87

Wilkin, J., and Hunter, E. (2013). An assessment of the skill of real-time models of Middle Atlantic Bight continental shelf circulation. *J. Geophys. Res. Oceans* 118, 2919–2933. doi: 10.1002/jgrc.20223

Wilkin, J. L., Arango, H. G., Haidvogel, D. B., Lichtenwalner, C. S., Glenn, S. M., and Hedström, K. S. (2005). A regional ocean modeling system for the long-term ecosystem observatory. *J. Geophys. Res.* 110:C06S91. doi: 10.1029/2003JC002218

Yang, Y., Cowen, L. L., and Costa, M. (2018). Is ocean reflectance acquired by citizen scientists robust for science applications? *Remote Sens.* 10:835. doi: 10.3390/rs10060835

Yu, P., Kurapov, A. L., Egbert, G. D., Allen, J. S., and Kosro, P. M. (2012). Variational assimilation of HF radar surface currents in a coastal ocean model off Oregon. *Ocean Model.* 49-50, 86–104. doi: 10.1016/j.ocemod.2012.03.001

Zhang, Y. J., Stanev, E., and Grashorn, S. (2016a). Unstructured-grid model for the North Sea and Baltic Sea: validation against observations. *Ocean Model.* 97, 91–108. doi: 10.1016/j.ocemod.2015.11.009

Zhang, Y. J., Ye, F., Stanev, E. V., and Grashorn, S. (2016b). Seamless cross-scale modelling with SCHISM. *Ocean Model.* 102, 64–81. doi: 10.1016/j.ocemod.2016.05.002

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frontiers in Marine Science

REVIEW
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Requirements for a Coastal Hazards Observing System

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Coastal zones are highly dynamical systems affected by a variety of natural and anthropogenic forcing factors that include sea level rise, extreme events, local oceanic and atmospheric processes, ground subsidence, etc. However, so far, they remain poorly monitored on a global scale. To better understand changes affecting world coastal zones and to provide crucial information to decision-makers involved in adaptation to and mitigation of environmental risks, coastal observations of various types need to be collected and analyzed. In this white paper, we first discuss the main forcing agents acting on coastal regions (e.g., sea level, winds, waves and currents, river runoff, sediment supply and transport, vertical land motions, land use) and the induced coastal response (e.g., shoreline position, estuaries morphology, land topography at the land–sea interface and coastal bathymetry). We identify a number of space-based observational needs that have to be addressed in the near future to understand coastal zone evolution. Among these, improved monitoring of coastal sea level by satellite altimetry techniques is recognized as high priority. Classical altimeter data in the coastal zone are adversely affected by land contamination with degraded range and geophysical corrections. However, recent progress in coastal altimetry data processing and multi-sensor data synergy, offers new perspective to measure sea level change very close to the coast. This issue is discussed in much detail in this paper, including the development of a global coastal sea-level and sea state climate record with mission consistent coastal processing and products dedicated to coastal regimes. Finally, we present a new promising technology based on the use of Signals of Opportunity (SoOp), i.e., communication satellite transmissions that are reutilized as illumination sources in a bistatic radar configuration, for measuring coastal sea level. Since SoOp technology requires only receiver technology to be placed in orbit, small satellite platforms could be used, enabling a constellation to achieve high spatio-temporal resolutions of sea level in coastal zones.

Keywords: SAR/Delay-Doppler Radar Altimetry, retracking, coastal zone, sea level, coastal modeling, storm surge, hazards, Reflectometry Wideband Signals of Opportunity (GNSS-R/W-SoOp)

INTRODUCTION

Today about 600 million people (mostly concentrated in several of the world's largest megacities) live very close to the sea at an altitude less than 10 m and this number is expected to double by 2060 (Nicholls, 2010). In many of these regions, populations are exposed to a variety of natural hazards (e.g., extreme weather such as damaging cyclones and their associated storm surges), to the effects of global climate change (e.g., sea level rise), and to the impacts of human activities (e.g., urbanization). In low-lying coastal areas, several of these factors may combine to increase the risks significantly to coastal populations. For example, the risk of flooding and coastal erosion during extreme events, and of salt-water intrusion into rivers and coastal aquifers on which people depend, is exacerbated by climate-related sea level rise. Its negative impacts are amplified by land subsidence, caused by ground-water extraction in coastal megacities or oil exploration on shallow shelves. Coastal zones are already suffering ecological and biological stresses, for example poor water quality, pollution, destruction of marine ecosystems, etc. as a result of these strong anthropogenic pressures.

It has been reported that 24% of the world's sandy beaches are eroding at a rate over 0.5 m per year (Luijendijk et al., 2018). This raises the issue of understanding the underlying causes. Shoreline change and coastal flooding are critical concerns for many coasts worldwide and they are expected to be strongly aggravated by sea-level rise (e.g., Ranasinghe, 2016; Arns et al., 2017; Vitousek et al., 2017; Vousdoukas et al., 2018). In the future, these risks are expected to increase due to the combined effects of climate change and human activities. The response of coastal environments to natural and anthropogenic forcing factors (including climate change) depends on the characteristics of the forcing agents, as well as on the internal properties of the coastal systems. These remain poorly known and mostly un-surveyed at global scale. **Figure 1** summarizes the many processes currently affecting coastal zones.

Various types of long-term observations need to be collected and analyzed within an integrated framework, in order to: (1) gain information about the evolution of the coastal zones during the past few decades; (2) improve knowledge about the causes of this evolution, in particular sea level change, and (3) provide information to decision-makers and coastal zone managers.

In this article, we address the issue of coastal zones evolution in response to a variety of forcing agents. We propose a series of recommendations about systematic monitoring of coastal zones and associated observing systems needed to improve our understanding about the processes involved (see section "Monitoring Coastal Zones With Multiple Observing Systems"). However, monitoring of sea level in coastal areas is the main focus of the paper. Thus after a brief overview of the multiple factors affecting coastal zones and the need for monitoring them (see section "Monitoring Coastal Zones With Multiple Observing Systems"), a large part of the paper is devoted to the use of satellite altimetry to provide robust estimates of rates as close to the coast as possible (see section "Coastal Zone Altimetry Processing and Exploitation: Progress and Outlook for the Next Decade"). We also address new types of observations, namely the Ocean Surface Topography Using Wideband Signals of Opportunity (OST W-SoOp), which draws its heritage from altimetry concepts using the Global Navigation Satellite System Reflectometry (GNSS-R) technology and which is able to complement altimetry-based sea level measurements in coastal areas (see section "Wideband Signals of Opportunity Reflectometry for Coastal Ocean Applications"). In Section

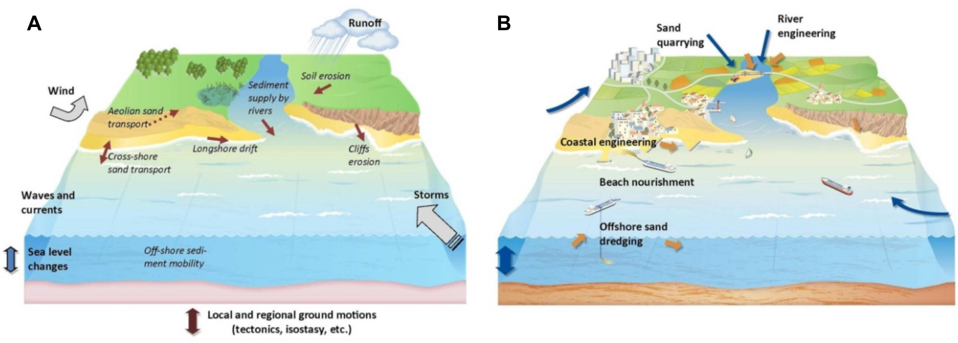

FIGURE 1 | Natural **(A)** and anthropogenic **(B)** processes affecting shoreline changes (source: Cazenave and Le Cozannet, 2014).

"Opportunities for Integration," we discuss opportunities for integration and in Section "End Users Engagement," we scrutinize how to engage end users.

MONITORING COASTAL ZONES WITH MULTIPLE OBSERVING SYSTEMS

Context

Coastal zones, where a large proportion of the world population lives, are under serious threat because of extreme events and flooding, urbanization, sand extraction, salinization of estuaries and of coastal aquifers, and shoreline erosion and retreat. These hazards are expected to increase due to the combined effects of sea level rise, climate change, and increase in human activities. The response of coastal environments to natural and direct/indirect anthropogenic forcing factors depend on the characteristics of the forcing agents, as well as on the internal properties of the highly dynamical coastal systems. The latter remain poorly known and mostly un-surveyed at a global scale. Coastal observations of various types need to be collected and analyzed to better understand changes affecting coastal zones and provide crucial information to decision-makers involved in adaptation and mitigation of environmental risks. The near-global observations from space of many coastal parameters are a fundamental complement to existing *in situ* coastal observing systems, which still remains relatively sparse (e.g., regional tide gauge networks, moorings, ship surveys, gliders) (Cazenave et al., 2017; Woodworth et al., 2017). In this section, we briefly review the need for systematic monitoring of the world coastal zones, with an emphasis on space observations of both forcing agents (e.g., sea level, winds, waves and currents, river runoff, sediment supply and transport, vertical land motions, land use) and coastal responses (e.g., shoreline position, estuaries morphology, land topography at the land–sea interface and coastal bathymetry).

Forcing Agents Affecting Coastal Zones and Observational Needs

Forcing agents acting on coastal zones include sea level change, extreme events, winds, waves and currents, vertical ground motions, sediment supply, river runoff, land use change and urbanization.

Mean Coastal Sea Level Variability and Change

Global mean sea level is currently rising and even accelerating (e.g., Cazenave et al., 2018; The WCRP Global Sea Level Budget Group, 2018). While satellite altimetry has considerably improved our understanding of sea level variations at global and regional scales, this is not the case for coastal areas. In terms of impacts, what counts at the coast is the total relative sea level, i.e., the sum of global mean rise, on which regional variability is superimposed over local ocean processes (e.g., shelf currents, tides, surges, ocean surface waves), and vertical land motions. Satellite altimetry, optimized for the open ocean, performs poorly in the last 20 km to the coast due to perturbing factors, including land contamination. Recent progress in reprocessing radar waveforms in coastal areas, and the use of new altimetry techniques (e.g., Ka–band altimetry and SAR mode), have enabled the development of new coastal altimetry datasets (Birol et al., 2017; Passaro et al., 2018). However, these products remain inhomogeneous in space and time, and efforts are needed to construct a consistent global gridded coastal altimetry database. A detailed discussion of coastal sea level monitoring by satellite altimetry is provided in Section "Coastal Zone Altimetry Processing and Exploitation: Progress and Outlook for the Next Decade."

Extreme Water Levels

Extreme water levels result from a number of oceanic, atmospheric, and terrestrial processes. They generally occur from the combination of high astronomical tides, large storm surges, high mean sea level and strong waves. However, the importance of each of these factors varies around the world. Extreme levels due to the astronomical tides occur on timescales of approximately 4.5 and 18.6 years, respectively. Those due to storm surges and surface waves at mid and high latitudes occur primarily during winter. Seasonal variations result from surge-related water level changes above the mean sea level 'baseline.' At inter-annual to decadal timescale, there is strong influence of large-scale modes of climate variability, such as El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO) or the North Atlantic Oscillation (NAO). There are also higher frequency oscillations (in the order of a few minutes) that result from fast, abrupt changes in the atmospheric conditions combined with an amplified topographic response (i.e., seiches or meteo-tsunamis).

An example of extreme water level due to tide and surge is shown in **Figure 2**.

A great deal of evidence show that extreme water levels depend on changes in the mean sea level (Menéndez and Woodworth, 2010; Woodworth et al., 2011). This is illustrated in **Figure 3** showing that trends in either extremes (99-percentiles) in total water level (**Figure 3A**), or in skew surges (**Figure 3C**) can be largely removed if you subtract the mean sea level (not 100%, however) (**Figures 3B,D** respectively).

However, changes in extremes also depend on other processes, such as changes in the climatology of storm surges and surface waves. Because of different generation mechanisms, storm surges caused by tropical cyclones are different than those produced by higher-latitude storms. Tropical storm surges tend to be of smaller spatial scale, and shorter duration, but are much larger in amplitude. Valuable sources of information on sea level extreme events come from the data banks of tide gauge records collected by the University of Hawaii Sea Level Center (UHSLC) and the British Oceanographic Data Centre (BODC), for the Global Sea Level Observing System (GLOSS, a program from the Intergovernmental Oceanographic Commission of United Nation Educational, Scientific and Cultural Organization – UNESCO; IOC, 2012). The most complete sea level data set assembled to date, combined from governmental and research sources, is called GESLA-2 (Woodworth et al., 2016).

Vertical Land Motions

At the coast, vertical land motions cause relative sea level change. These have different origins. For example, in active tectonic and volcanic regions, the Earth's crust suffers important vertical displacements (e.g., Wöppelmann and Marcos, 2016). In other regions, natural causes (e.g., sediment loading in river deltas) or human activities (ground water pumping and oil/gas extraction) may give rise to significant ground subsidence that amplifies climate-related sea level rise (e.g., Raucoules et al., 2013). Post-glacial rebound, the visco-elastic response of the Earth crust to last deglaciation, also called "Glacial Isostatic Adjustment" (GIA), is another process that produces vertical land movements, in particular in high-latitude regions (Peltier, 2004; Tamisiea, 2011).

Faced with the difficulty of modeling all the relevant geophysical processes that cause vertical displacements in coastal zones, both globally and accurately, space-based geodetic techniques are an alternative approach. Available Global Navigation Satellite Systems (GNSS) can indeed help estimating land motions, in particular nearby tide gauges (Wöppelmann et al., 2007). However, presently, less than 14% of GLOSS tide-gauge stations are directly equipped with a permanent GNSS station (see Ponte et al., submitted to this OceanObs'19 FMS Special Issue).

Another important limitation is that even extensive GNSS networks, such as those deployed in Japan or North America, are essentially a collection of point measurements that are sparse compared to the short spatial scales of vertical land motion along many coastlines, where information is needed to determine relative sea level change. Brooks et al. (2007) proposed to combine point wise but accurate geocentric measurements

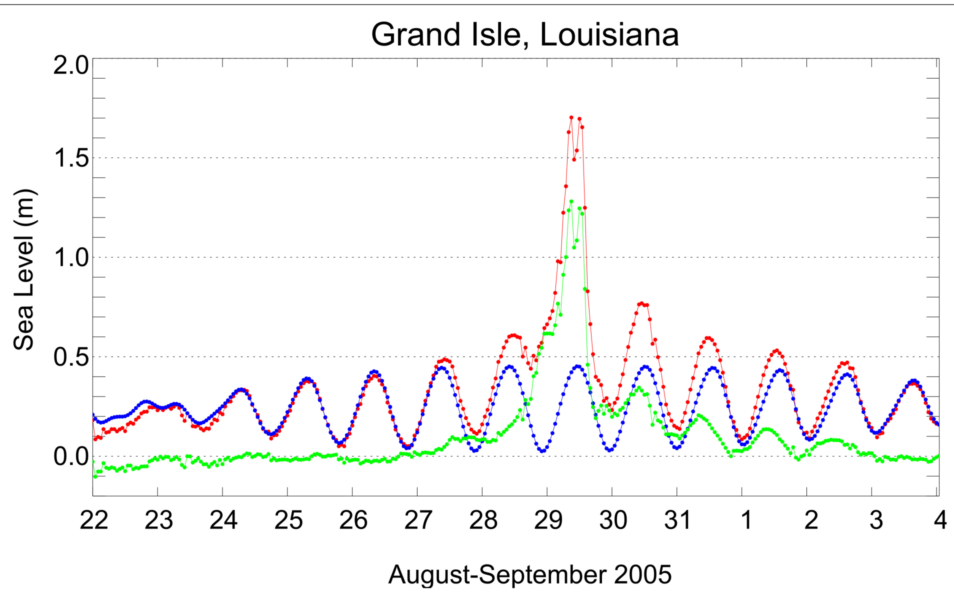

FIGURE 2 | Observed (red), tidal (blue), and meteorological (green) variations of sea level at Grand Isle, Louisiana during Hurricane Katrina, 28–30, August 2005. From Pugh and Woodworth (2014).

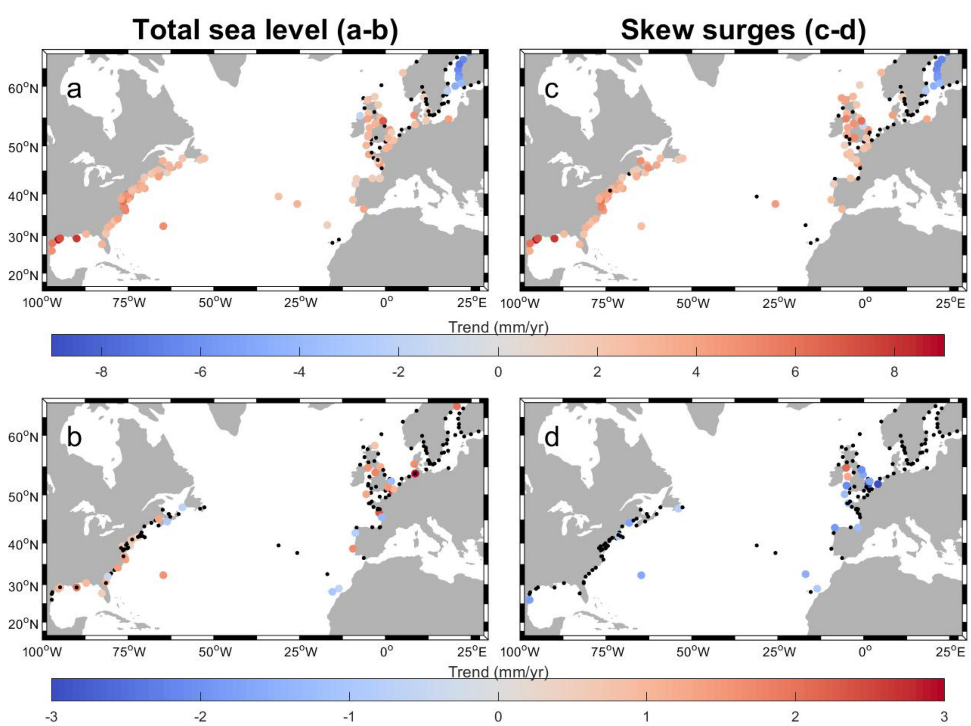

FIGURE 3 | (a) Linear trends of annual 99th percentiles of total sea level and **(b)** with median removed. **(c)** Linear trends of annual 99th percentiles of skew surges and **(d)** with median removed. Tide gauge data from 1960 to present are used. Black dots indicate where the trends are not significant. From Woodworth et al. (2019).

from GNSS with spatially dense but relative (to an arbitrary point on land) measurements from Interferometric Synthetic Aperture Radar (InSAR; e.g., Massonnet and Feigl, 1998). They show that the combined GNSS and InSAR products yield deeper physical understanding and predictive power for beach morphology evolution. Subsequent studies have explored various methods based on InSAR measurements to further assess its applicability in different coastal environments (Raucoules et al., 2013; Wöppelmann et al., 2013; Le Cozannet et al., 2015), confirming its usefulness in sea level studies. InSAR, being more reliable in urban (or arid) areas than in vegetated areas, is particularly efficient for measuring surface displacements in coastal megacities. For mapping long-term deformation with a precision consistent with the sea-level rise rate, the performance of InSAR is related to the number of images in the archive (e.g., about 50 images are required on a multi-year period for reaching ~1 mm/year precision). However, no project exists at global scale to combine GNSS and InSAR methods.

Vertical land motions at the coast can also be derived from the difference between altimetry-based and tide-gauge-based sea level trends. Although this approach is less accurate than direct ground motion measurements by GNSS, it represents an interesting alternative at tide-gauge sites not equipped with GNSS antennas. This topic is discussed in Section "Coastal Altimetry and Tide Gauges for Solving Vertical Land Motion."

Waves and Winds in Coastal Zones

The retrieval of waves and winds in the coastal zone is as yet not as mature as sea level measurements. Yet recent studies have shown that trends in wave set-up and swash, which represent the wind-wave contributions to total water level at the coast, can significantly alter sea level changes at the coast over interannual-to-multidecadal timescales (e.g., Melet et al., 2018). Passaro et al. (2015b) showed that altimetry-based near coast estimations of Significant Wave Height (SWH) at 20-Hz frequency based on the ALES retracking (Passaro et al., 2014) are generally well correlated with buoy data. Besides, the spatial variation of the wave field being highly dependent on the local bathymetry, improved coastal bathymetry is also required (see subsection "Digital Elevation Models and Bathymetry"). In addition, wave setup and swash depend on the foreshore beach slope. While sandy beaches are considered as especially vulnerable to sea level rise, no estimates of foreshore beach slopes are available worldwide yet (Luijendijk et al., 2018; Vousdoukas et al., 2018). These slopes vary in space and time, and are required to refine estimates of wave setup and swash.

Although no study exists in coastal areas, several studies have highlighted the interest of using altimeter-derived winds over open ocean for climate studies. Young et al. (2011) have shown that altimeter-derived winds indicate a global increase of sea-surface wind field of roughly 3–4 cm/s/year (from 1991 to 2008) with large regional patterns between 1 cm/s/year and

11 cm/s/year. Similar sea-surface wind speed increase have been detected by Zheng et al. (2016) from Cross-Calibrated, Multi-Platform (CCMP) data, not based on altimetry measurements, but confirming the ability of altimetry measurements to measure the long-term evolution of sea surface winds. Further studies are necessary to better characterize and understand the long-term evolution and uncertainties of altimeter-based sea-surface winds in coastal areas. SAR and scatterometry data would also be useful in the interpretation of the results.

Sediment Transport, River Discharge, and Land Cover Change

Other forcing agents acting in coastal zones include river runoff, sediment supply, and land use change. Over the last decades, human activities have strongly modified river runoff and sediment transport, which greatly influences coastal erosion.

Sediment transport

The monitoring of Suspended Particulate Matter (SPM) in coastal waters is essential to understand the evolution of coastal zones (Ouillon et al., 2004; Warrick et al., 2004; Loisel et al., 2014). Solid water discharge from rivers, terrestrial matter from shore erosion, and re-suspension of bottom sediments occurring in shallow waters under local wind-waves and swell action, represent the main sources of suspended particles in coastal waters. Organic particles from terrestrial origin, or produced locally by biogeochemical processes also contribute to SPM. SPM variability is tightly linked to coastal erosion and accretion processes and then has a direct impact on the coastline evolution. Forecasting SPM dynamics in response to natural or anthropogenic forcing is crucial to better adapt to present and future coastal changes. Such an objective can only be achieved by combining modeling and observation efforts. Ocean-color satellite observations can provide information on the SPM variability of surface waters at relevant spatio-temporal scales. These data, which can be collected over long time periods, represent a valuable source of information to better constrain sediment transport models. While past ocean-color sensors were able to collect observations at the spatial resolution of 1 km × 1 km, the new ocean-color sensors generation, such as OLCI on Sentinel-3, allows sampling at a much better spatial resolution (i.e., 300 m × 300 m). Also, high spatial resolution sensors (10–60 m) such as OLI on Landsat-8 or MSI on Sentinel-2, both originally developed for land observation, have a sufficient radiometric resolution to be used for SPM assessment. Because current remote sensing observations only provide information about the surface layer, the assessment of the total load of sediment integrated on the whole water column requires the development of synergic approaches combining passive and active (i.e., LiDAR) remote sensing, and modeling.

River runoff

Accurate estimates of river runoff and sediment delivery to the coastal zone are also crucial. River Water Discharge (RWD) is one of the major processes that affect environmental conditions (such as currents and hydrography) in coastal waters. It reflects the drainage basin area dynamics and is a function of parameters such as geology, relief, precipitation, vegetation, climate and human influences. The RWD provides fresh waters that affect mixing and circulation processes in estuaries, thus modifying geomorphological and geochemical properties of the coast (Milliman and Farnsworth, 2013). Besides, building of reservoirs on rivers decrease water and sediment fluxes to the coast (Syvitski et al., 2005). Another important consequence of RWD control is the high flow amplitudes reduction, which decreases the carrying capacity for SPM, and modifies the seasonal estuarine circulation patterns and salinity distributions. All of these changes can greatly influence coastal erosion, the benthic environments, coral reefs, sea-grass communities, and coastal fisheries. Quantifying accurately fluvial delivery to the coastal zone is therefore crucial. Long-term high-resolution RWD and SPM measurements – in both time and space – are needed to assess the impact of global change on coastal zones.

Satellite altimetry now routinely measures water level on land from which river discharge can be derived, in particular over ungauged or poorly gauged hydrological basins (Crétaux et al., 2018). River discharge for medium size basins ($<$10,000 km^2) is also indirectly estimated from satellite images in the visible and near infrared spectrum (e.g., MODerate-resolution Imaging Spectroradiometer – MODIS) (Tarpanelli et al., 2015). The Surface Water and Ocean Topography (SWOT) satellite mission planned for launch in 2021 will improve the characterization of global runoff processes with a $\sim$50 m resolution threshold.

Coastal Responses and Observational Needs

Depending on the time-scale of processes acting in coastal zones (from extreme events to long-term sea level rise), different types of observations are required to monitor and understand the response of coastal zones to the forcing agents and associated shoreline changes.

Shoreline Changes

Scientists and coastal managers concerned with shoreline changes focus on three different types of processes: (1) extreme events such as major storms or cyclones, (2) seasonal to decadal coastline variability, and (3) decadal to multidecadal shoreline changes.

Depending on the process of interest, different types of data and observational strategies are needed. For extreme events, the priority is given to comparing pre- and post-crisis coastal morphologies. In this case, both a background observational framework and a capacity to monitor the coastal sites just after the events are needed. Such capabilities are presently more or less available from both the space and *in situ* components of coastal observatories (international charter for disaster; post-crisis special missions organized by coastal communities).

Monitoring seasonal to longer-term changes requires high-resolution observations in space and time. However, the actual specifications depend on the coastal site of interest. For example, multi-decadal surveys in highly dynamic deltas can benefit from medium resolution data (e.g., Landsat data), which can be analyzed using a semi-automatic procedure (Luijendijk et al., 2018). However, most shorelines around the world are currently evolving at rates in the order of ±1 m/year or less (Bird, 1985).

With pioneering global coastal evolution datasets being made available today (Luijendijk et al., 2018), meeting local user needs in terms of precision and accuracy (below 1 m/year) has become a next challenge for Earth Observations (EO).

Digital Elevation Models and Bathymetry

High resolution Digital Elevation Models (DEMs) and coastal bathymetric data are critical datasets for a number of applications in coastal zones, including accurate modeling of flooding during storm surges, and quantification of coastal morphological changes due to sedimentary processes or human interventions. High-resolution bathymetric and topographic LiDAR techniques have allowed important progresses over the last decade, but still require post-processing to remove trees and cars from the raw data. However, the lack of repetitiveness in current LiDAR acquisitions is presently limiting the applications, especially in highly dynamic coastal zones such as beaches, marshes, and estuaries. Further acquisition of high-resolution topography, near-shore bathymetry and foreshore beach slopes data is an observational priority, especially along densely populated coastlines. A second priority is the development of methods to cover the need for repeated acquisitions in highly dynamic areas. While this seems technically feasible, further research is needed to meet the users' requirements in terms of temporal resolution, especially in near-shore areas.

Summary

To better understand how coastal zones react to various perturbing factors and change through time, a number of observing systems, either space-based, airborne or *in situ* should be implemented and combined. We summarize below a (non-exhaustive) series of observational needs related to the topics addressed in this section:

- Ensure that the global and regional monitoring networks of extreme sea levels are completed to their full technical requirements.
- Ensure that a global sea level database such as GESLA-2 is maintained and extended in the future.
- Ensure that extreme water levels observations are acquired in areas unaffected by the wave setup.
- Increase the number of GNSS stations co-located with tide gauges for monitoring vertical land motions (Woodworth et al., 2017).
- Develop precise positioning capabilities in coastal areas combining GNSS and InSAR approaches to monitor local to regional land motions.
- Altimetry can provide wave height, wind speed and sea level at the same time. However, systematic monitoring of the fine-scale variations of these parameters at the coast is still lacking. The high-resolution wave field in the coastal band is also relevant, as it helps developing more realistic wave models that can be used to estimate wave setup. R&D investigations using archived and coming altimeter data sets (in particular with the new SAR mode) need to be conducted. Moreover, multi-sensor approach for wind and waves in the coastal zone using altimetry, SAR and scatterometry where ground-truth is available would be highly useful.
- Coherent and homogenized SPM time series over the global coastal region should be collected from past and present space-based ocean-color data. This task requires inter-calibration between the different sensors, as well as the development of common atmospheric and bio-optical algorithms. Uncertainty maps should also be provided. Fusion of high-spatial-low-spectral and medium-spatial-high-spectral resolutions sensors should be undertaken to better sample the coastal environment at the relevant scales.
- Long-term high-resolution observations of river discharge, ground water discharge, SPM in global coastal zones are highly needed.
- The full potential of remote sensing for monitoring shoreline changes has not been fully investigated yet. Use of SAR data to monitor shorelines changes in tropical areas has been explored but the resolution of this data set (about 30 m for ASAR on-board Envisat) remains too limited. More recent high-resolution sensors (e.g., Cosmo-Skymed) and improvements in orbital parameters control (e.g., TerraSAR-X) offer useful alternative. Research to automatize the precise georectification of images (beyond what is classically provided by current workflows) and, ultimately, to retrieve shoreline proxies automatically would be much beneficial to the community.
- A high spatio-temporal resolution continuous marine-land topography and bathymetry database, with height precision better than 20 cm is needed. However, lower resolution datasets such as those that can be produced with Sentinel 2 or other data may still be useful for understanding coastal evolution (e.g., Poupardin et al., 2016).

Concerning that latter issue, present-day information on the evolution of coastal zones is currently acquired at local to regional scales by coastal observatories, which act as a means of transferring information between science, operational observations (including space-based), and coastal stakeholders (Suanez et al., 2012). Presently, the existing information at national, multinational, and global scales originates from these entities (e.g., Eurosion, 2004). However, different coastal observatories are far from having the same standards (resource datasets, including from satellite observations, workflows, procedures, and objectives), so that the information that currently exists is often extremely heterogeneous. Networks of coastal observatories are being established in different countries to resolve this issue.

COASTAL ZONE ALTIMETRY PROCESSING AND EXPLOITATION: PROGRESS AND OUTLOOK FOR THE NEXT DECADE

Context

Coastal Altimetry is the extension of open ocean altimetry into the oceanic coastal zone. It has had a steady progress in recent years and has become a recognized mission target for present and future satellite altimeters (Vignudelli et al., 2011; Cipollini et al., 2017). Compared to conventional Ku band, Low Resolution Model (LRM) altimetry missions launched since the early 1990s (ERS, Topex/Poseidon and Jason series, Envisat), the SARAL/AltiKa mission, operating in Ka band, CryoSat-2 operating in Ku band but in Synthetic Aperture Radar (SAR) [also called Delay-Doppler Altimeter (DDA)] mode and in the interferometric mode (SARin) and Sentinel-3A/B operating in Ku and C bands in SAR mode, have proved their ability to obtain more precise and accurate measurements of sea surface heights. Because of their reduced footprint, measurement geometry and dedicated algorithms for both processing at level 1 and level 2, data can be acquired closer to the coastline with improving performances. Indeed, the most important achievement of Coastal Altimetry research in the last 10 years has been the reduction of the data gap near the coast, which is today less than 5 km (Cipollini et al., 2017).

Coastal altimetry has some complications beyond open ocean altimetry work. Two issues that have already been extensively studied are land interference and inhomogeneity of radar backscatter. As a consequence of the previous factors the waveform is distorted. Re-tracking algorithms applied to the radar echoes need to recognize and mitigate these distortions.

Dedicated corrections to correct altimeter ranges in the coastal zone are also crucial. All corrections in standard altimetry were optimized for the open ocean. They do not account for specificities of the coastal zone [bathymetry for tidal and atmospheric loading models; land interference for radiometer used to estimate water vapor; sea state variability for the sea state bias (SSB) correction].

Retracking Conventional and SAR Mode Altimetry

So far, quality and quantity of altimeter data retrieved in the coastal zone have improved thanks to new specific processing applied to conventional altimetry and use of the new DDA mode, and fitting processing. For conventional altimetry, new sub-waveform partitioning and fitting have been designed to tackle waveform inhomogeneities in the satellite footprint typical of coastal waters, due to presence of land or patches of calm water. This novel approach restricts the fitting to a portion of the reflected signal (Deng and Featherstone, 2006; Yang et al., 2012; Passaro et al., 2014, 2018; Dinardo et al., 2017; Roscher et al., 2017; Peng and Deng, 2018). A successful way of selecting this portion is based on an adaptive algorithm, which depends on the sea state (as in Passaro et al., 2014), which strongly influences the noise performances of an altimeter, leading to a significant improvement in terms of quality and quantity of the data retrievals, while improving the description of the middle scales of variability (10–80 km) in the open ocean as well (Smith et al., 2017).

A first example is provided in Passaro et al. (2015a) for the sea level estimated from the Adaptive Leading Edge Subwaveform (ALES) retracker, evaluated in coastal areas against open ocean products from the European Space Agency Sea Level Climate Change Initiative (ESA SL_cci) and Radar Altimetry Database (RADS), not tailored for coastal exploitation. The standard deviations and root mean square differences of the sea surface height anomalies (SSHa) from ALES are smaller than for the SL_cci and the RADS products (see **Figure 4**). A second example is provided in Roscher et al. (2017) by the Spatio-Temporal Altimetry Retracking (STAR) retracker, where sub-waveform analysis was modified through sparse representation and conditional random field (CRF) modeling. The latter compares well to the ALES sub-waveform method, with similar SSHa quality in open ocean and coastal zone (see **Figure 5**).

A step forward has been made with the DDA technology on CryoSat-2 since 2010 and Sentinel-3 since 2016. Its novelty consists in exploiting the different Doppler shift experienced by different rows of the altimeter antenna beam,

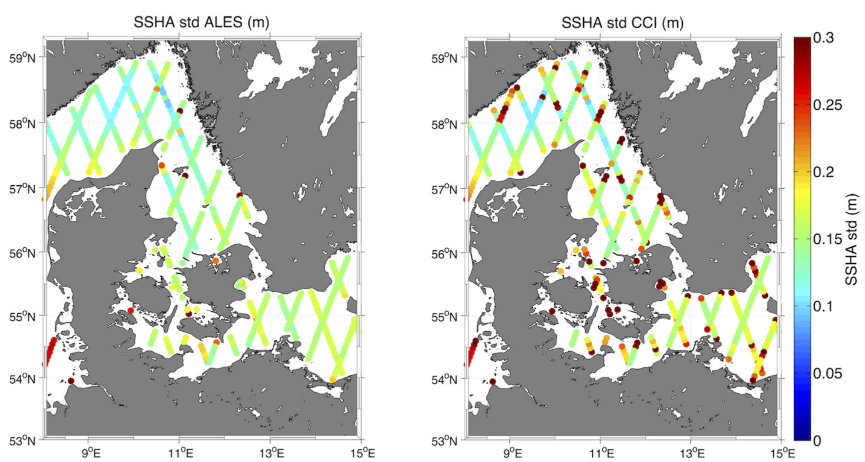

FIGURE 4 | Comparison between **(Left)** ALES reprocessed and **(Right)** Envisat SL_cci data sets in terms of standard deviation of the Sea Surface Height Anomaly time series for each 1 Hz location (adapted from Passaro et al., 2015a, with permission).

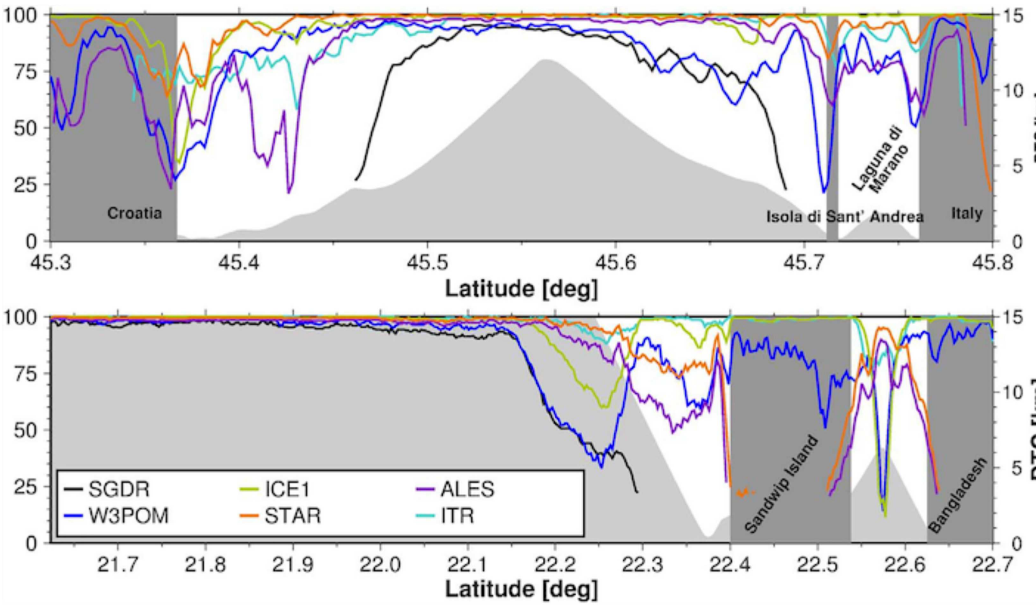

FIGURE 5 | Percentage of the total number of available Jason-2 cycles (227) after applying outlier detection and minimum number of cycles requirement. **(Top)** Study site at the Gulf of Trieste. **(Bottom)** Study site at the coast of Bangladesh. The distance to the nearest coastline is provided in light gray. The colored lines correspond to the different retrackers mentioned by their acronym in the insert (adapted from Roscher et al., 2017, with permission).

depending on the along-track angle with respect to nadir. It provides an improved along-track resolution of ∼300 m, while the across-track resolution is the same as in conventional altimetry. The coverage is improved in coastal region where conventional altimeters echoes are impacted by land contamination in both directions. Moreover, DDA has an enhanced signal-to-noise ratio to retrieve fine-scale oceanographic features. In open ocean both accuracy and precision are higher in DDA than in Pseudo LRM (PLRM), or Reduced SAR (RDSAR) (Fenoglio-Marc et al., 2015a; Buchhaupt et al., 2017). PLRM/RDSAR are derived from the Full Bit Rate (FBR) data by processing the pulse-limited echoes incoherently, like in the conventional LRM concept (Smith and Scharroo, 2015).

As for conventional and DDA altimetry, dedicated processing has been developed to improve the data in the coastal zone. This includes both fully focused SAR (Egido and Smith, 2017) and enhanced unfocused SAR processing. The standard unfocused SAR processing baseline consists of ground cell gridding at 20 Hz, Doppler Beam Forming, Doppler Beam Stacking, Slant Range Compensation, Range Compression and Multilooking (Raney, 1998; Cullen and Wingham, 2002) and of the open ocean SAMOSA SAR waveform model (Ray et al., 2015) in its formulation with zero- and first-order term (SAMOSA2). For coastal zone, Dinardo et al. (2017) extend the processing baseline SAMOSA2 to SAMOSA+, enhancing the processing with a set of options specifically tailored for the coastal domain both at the waveform generation level and in the retracking step. In coastal zone DDA is less noisy than PLRM/RDSAR and more data are retained by the outlier rejection as shown in **Figure 6**. Similarly, the standard deviation of SSHa, which increases near coast, is the smallest for DDA data processed with SAMOSA+ and within the expected range until 2–3 km from the coast. Standard deviation of differences and absolute biases between the SSHa and tide-gauge data are on the order of few centimeters (Bonnefond et al., 2018a; Fenoglio et al., 2019). Best results come from CryoSat-2 and Sentinel-3A SAR altimetry processed with SAMOSA+ at the Grid Processing On Demand (GPOD) service at ESRIN[1]. *In situ* and model validation of SWH and wind speed SAR show improvement with the new SAR data (Staneva et al., 2016; Wiese et al., 2018).

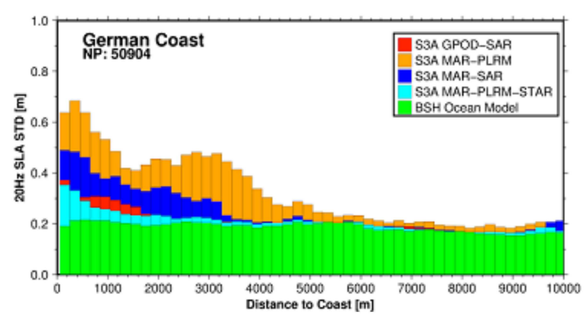

FIGURE 6 | Sea level anomaly at 20 Hz standard deviation in 200 m bins of distance to coast for different Sentinel-3A processors and the BSH model along the German coast. The Sentinel-3A SAR altimetry processed with SAMOSA+ at the Grid Processing On Demand (GPOD) service at ESRIN exhibit the smallest standard deviation (adapted from Fenoglio et al., 2019, with permission).

[1] https://gpod.eo.esa.int

SARin Mode and Fully Focused SAR Altimetry

The fully focused SAR (FF-SAR) processing technique promises an along-track resolution of 0.5 m for typical SAR altimeters (Egido and Smith, 2017), instead of the 300-m resolution of the unfocused DDA processing. Also relevant for coastal zone, but scarcely investigated in this area is the DDA interferometry (SARin), which permits to extract spatial and temporal derivatives of water levels, providing an entirely new observable area. Few studies in coastal zone so far use SARin CryoSat-2 data (see Bouffard et al., 2018 and Parrinello et al., 2018 for a recent review). Idžanović et al. (2017) selected Norwegian tide gauges close to CryoSat-2 tracks with data collected in SARin mode (**Figure 7**) and found that SARin data processed as SAR has higher correlation and better RMS with *in situ* on the rugged coast of Norway compared with conventional altimetry. Abulaitijiang et al. (2015) fully exploited the SARin interferometry and showed that data from 0 to 7 km inland can be re-allocated to the coast using the Off Nadir Range correction (ONR) (**Figure 8**). Data further in-land from 7 to 14 km can also be re-allocated to the coast by ONR and Phase Ambiguity correction (PA).

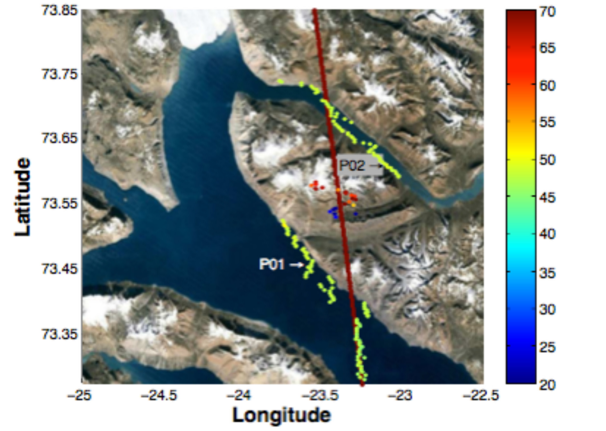

FIGURE 8 | Ascending track crossing the Fjords of Eastern Greenland. Dark red track correspond to the satellite nadir. Scattered points are relocated positions after the ONR corrections are applied. Two points are marked by P01 and P02 in the figure. The elevations are referenced to WGS84 ellipsoid. Unit: meters (adapted from Abulaitijiang et al., 2015).

Geophysical Corrections

Together with accurate orbits and satellite-to-surface altimeter range retrievals, geophysical corrections, associated to coastal-oriented editing strategies (Vignudelli et al., 2005), are another crucial component in accurately deriving SSHa measurement at the coast. Much progress has been achieved in the last decade in retrieving accurate corrections over coastal and inland water regions, in particular the dry tropospheric correction (DTC) (Fernandes et al., 2013, 2014), the wet tropospheric correction (WTC) (Desportes et al., 2007; Brown, 2010; Fernandes et al., 2010, 2015; Fernandes and Lázaro, 2016, 2018) and ocean tides (Carrère et al., 2014). Regarding the WTC, increasing accuracy is obtained with the ERA5 atmospheric reanalysis from ECMWF, now provided at 1-h time sampling and also from the high frequency channels included in the microwave radiometers to be flown on Sentinel-6 and SWOT missions.

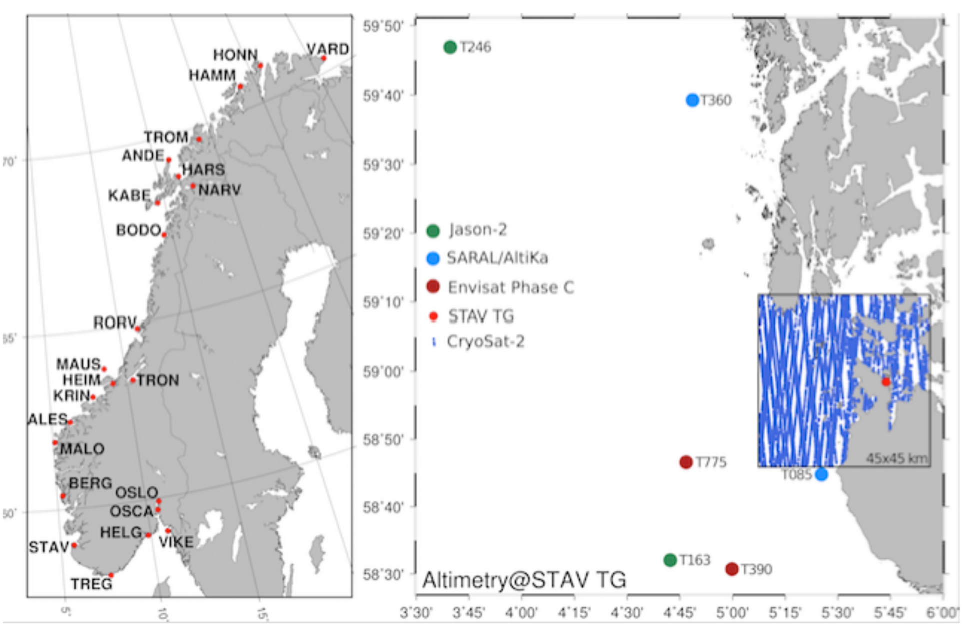

FIGURE 7 | The Norwegian tide gauges **(Left)** used in the study and example of CryoSat-2 tracks with data collected in SARin mode and near STAV station **(Right)**. Also shown are the closest Envisat, Jason-2 and SARAL/Altika ground points (adapted from Idžanović et al., 2017).

Regarding ocean tides, there is a need to increase the accuracy of tide models in the coastal zone, where they are known to be much less accurate than in the open ocean essentially because of the not-well-known bathymetry, which has a stronger impact in the shallow waters. In an iterative process it is crucial to improve the knowledge of the bathymetry and of the tide models with finer grids while approaching the coast. The ocean tide correction of the altimeter SSHa remain the largest error source of the whole altimetry end-to-end system in the coastal zone (Ray and Egbert, 2017; Toublanc et al., 2018).

Level 3 Altimetry Datasets

The development of dedicated altimetry datasets at level 2 (COASTALT, PEACHI) and level 3 (X-TRACK, ALES/COSTA, DUACS-HR) has been advancing toward the high along-track resolution and/or special processing to reduce noise and provide data near coastlines or in shallow shelf waters, offering an opportunity of exploitation for scientific applications. A table is published in Cipollini et al. (2017) and a regularly updated version is available at http://www.coastalt.eu/#datasets. Several studies compared these data sets with independent measurements (e.g., Gómez-Enri et al., 2016; Vu et al., 2018; Xu et al., 2018). Quality assessments for Sentinel-3A and CryoSat-2 (Bonnefond et al., 2018a; Fenoglio et al., 2019) and AltiKa data (Bonnefond et al., 2018b) have also been performed.

Storm surges are the major cause for coastal flooding, which can result in catastrophic damage to properties and loss of life in coastal communities. For example, over 1,800 people lost their lives during Hurricane Katrina, 2005 and many of those deaths were directly or indirectly caused by storm surge. Many coastal regions in the world are vulnerable to storm surges, with approximately 45% of the world's population living within 150 km of the coast. Thus it is important to utilize satellite altimetry to enhance our capabilities of observing storm surges to complement traditional tide-gauge networks as demonstrated in Madsen et al. (2015).

These data sets have been shown to be useful to monitor coastal storm surges (Han et al., 2012, 2017; Lillibridge et al., 2013; Antony et al., 2014; Chen et al., 2014; Fenoglio-Marc et al., 2015b) and to improve their forecasting (Madsen et al., 2015; De Biasio et al., 2016, 2017; Bajo et al., 2017; Li et al., 2018). While it is opportunistic for a single altimeter to capture a storm surge, a constellation of altimeter missions especially with wide-swath altimetry could significantly enhance the chance (Antony et al., 2014; Turki et al., 2015; Han, 2017; Han et al., 2017).

Study of coastal sea level variability and change is another application. Use of coastal altimetry dataset have revealed higher annual amplitudes in sea level in the presence of narrow coastal currents (Passaro et al., 2015a, 2016) improving the determination of coastal tides (Piccioni et al., 2018). The coastal altimetry data also helped in improving knowledge about spatio-temporal changes of the coastal ocean circulation (e.g., in the Mediterranean Sea: Birol and Delebecque, 2014; Jebri et al., 2016; in the eastern shelf of the Gulf of Tehuantepec: Salazar-Ceciliano et al., 2018). Another recent study by Dong et al. (2018) showed that both 20-Hz and 1-Hz along-track sea SSHa data can be used to extract coastal tidal mixing front signals. The value of improved altimeter data in detecting coastal SSHa sea level anomalies due to river discharge has been demonstrated by Gómez-Enri et al. (2017) and appears promising to study linkages between the land–sea domains (Piecuch et al., 2018). Another example of application concerns the characterization of mesoscale coastal dynamics in the southeastern Bay of Biscay (Spain) in combination with other remote sensing platforms and High-Frequency Radar observations (Rubio et al., 2018).

Coastal Altimetry and Tide Gauges for Solving Vertical Land Motion

As discussed in Section "Monitoring Coastal Zones With Multiple Observing Systems," knowledge of vertical land motions at the coast is important for several purposes. While GNSS techniques are the most direct approach to measure VLMs, differences between altimetry and tide gauge sea-level trends provide complementary information. Using monthly, 1-Hz sea level data from LRM altimetry missions and tide-gauge records, studies have shown that VLMs could be retrieved to 0.8 mm/year median accuracy (Wöppelmann and Marcos, 2016). Use of retracked coastal altimetry and DDA significantly improves the VLM estimates (Fenoglio et al., 2019).

Outlook and Recommendations

Great progress has been made during the past decade to improve SSHa measurements in the world's coastal zones for a variety of oceanographic and climate applications. These data have also been useful for high-resolution ocean modeling, either in comparison or assimilation modes. Models help "fill the sampling gap" with model-based dynamical downscaling. The challenge is the interpretation (and exploitation) of the extra resolution and the understanding of the signature due to the oceanographic content. Additionally, high-resolution Mean Dynamic Topography is essential in a regional data assimilative ocean prediction system to capture the subtleties of coastal mean circulation [e.g., Levin et al. (2018) produced their own local for the Middle Atlantic Bay].

The small scales characterizing the variability of the coastal ocean are driving the interest toward the use of SSHa at high rate (typically 20-Hz instead of 1-Hz). Coverage and sampling are being improved today by DDA and constellation of altimeters, but limitations in resolution and space–time sampling do not allow a systematic mapping. A wide-swath altimetry, which uses radar interferometry at near-nadir incidence angle (Rodriguez et al., 2018), needs to be used instead. Nadir altimetry will be part of the analysis, which goes from profile to surface observations. A further challenge is the improvement in DDA mode in SAR and SARin and the integration of past conventional altimetry, present DDA and future (swath-) altimetry observations to construct an extended and more complete sea level change record (Ablain et al., 2016; Legeais et al., 2018).

The main future goals of coastal altimetry are:

(1) Continuing improvement of waveform modeling and retracking, as well as of the geophysical corrections and of the mean sea surface in coastal regions.

(2) Assessing the performance of coastal altimetry with tide gauges measurements.
(3) Developing global multi-mission along-track and gridded sea level products including data in coastal zone to be used in regional and local studies.
(4) Contributing to coastal observing systems (for dynamics/level/sea state/extreme events) through data assimilation in models.
(5) Exploiting long time series of coastal altimetry data for coastal sea level and sea state climate.
(6) Contributing to the preparation of the SWOT mission.

Recommendations

For a number of scientific and societal applications, what is urgently needed is a global-scale coastal sea level data base that provides long-term (at least 2 decades-long) sea level records within 10–20 km to the coast, with as high as possible resolution (<1 km), based on retracked LRM altimetry and use of SAR technology, together with improved geophysical corrections adapted to coastal regions. Both along-track and gridded products (the latter derived from combining different missions) have to be provided. Ideally, what would be useful to end-users is a seamless multi-mission gridded sea level record (with associated uncertainty) from the open ocean to the coast, with global coverage and varying spatial resolution (25 km offshore, <1 km when approaching the coast). The user community also requests regular updates of this product.

WIDEBAND SIGNALS OF OPPORTUNITY REFLECTOMETRY FOR COASTAL OCEAN APPLICATIONS

Context

Since the early 1990s, development of high precision altimetry has witnessed great advances in our view of the oceanic circulation. One fundamental advance reveals that the oceanic circulation expands across a wide spectrum of temporal and spatial scales, from the basin scale of thousands of kilometers, mesoscale eddies of tens to hundreds of kilometers, down to sub-mesoscales of a few kilometers. All these scales are dynamic and energetic and play significant roles in ocean dynamics, climate variability, and biological and chemical processes, and are important to maritime operations. However, today's observations can resolve the circulations only down to large mesoscale scale eddies and temporal scales down to several days (e.g., Chelton et al., 2007).

To resolve the ocean circulation at spatial and temporal scales beyond what today's altimeters can resolve, new altimetry technologies are required. As discussed in section "Coastal Zone Altimetry Processing and Exploitation: Progress and Outlook for the Next Decade," DDA mode on new-generation of nadir altimeters significantly enhances the spatial resolution. Moreover, the SWOT mission, to be launched in 2021, will measure SSHa with a spatial resolution of order of 1 km, with a temporal revisit time driven by the 21-day repeat cycle and swath width (SWOT's 120-km-wide swath will result in overlapping measurements over most of the globe with an average revisit time of 11 days). Temporal repeat time can only be improved through launching more altimeters in appropriately phased orbits, a high-cost option with the current radar altimeter technology.

Here, an alternative approach is discussed, namely the Ocean Surface Topography Using Wideband Signals of Opportunity (OST W-SoOp), which draws its heritage from altimetry concepts using the Global Navigation Satellite System Reflectometry (GNSS-R) technology. This technique assumes that the ocean-scattered signal is composed of multiple ray-paths with a statistical distribution in delays. Cross-correlation between direct and reflected signal can be applied to estimate the fraction of scattered power within each arriving delay and Doppler bin, which map to areas on the scattering surface. The basic observable generated in reflectometry is the distribution of scattered power as a function of both delay and Doppler called the delay-Doppler map (DDM) (Zavorotny and Voronovich, 2000; Garrison et al., 2002). SSHa retrieval are derived by retracking the DDM.

Overview of Wideband Signals of Opportunity Reflectometry

Background: GNSS-R

The origin of SoOp altimetry can be traced back to the PARIS (Passive Reflectometry and Interferometry System) concept proposed by Martín-Neira (1993), in which GNSS transmitters were proposed as the signal source. The essential problem of the low bandwidth of the GNSS signals was identified with suggestion that opportunistic signals of "a few hundred MHz" could give scientifically useful cm-level accuracy in SSHa measurements. Key error sources were identified and a preliminary link budget performed for a design requiring a 4 m × 4 m antenna with a gain of 37 dB.

In the following decades, there was an increase in the promise of GNSS altimetry in providing an enhanced spatial and temporal sampling with a constellation of small, low-cost satellites employing passive receivers. The key difficulties of GNSS signal sources, however, have also been identified, namely (1) low bandwidth, (2) low transmitted power, (3) large ionospheric delay at L-band, and (4) large physical antenna dimensions to meet gain requirements. Subsequent studies and mission proposals have further quantified the effects of these limitations and designed systems incorporating necessary compromises to meet science requirements in light of these limitations.

Hajj and Zuffada (2003) considered coherence time, the spatial density of reflection points, and the effect of ionosphere and neutral atmosphere to evaluate space-borne GNSS altimetry. A rough error analysis predicted a 1-m error using a 23 dB antenna and 4 s of averaging. Spatial averaging over 100 km and temporal averaging over 4 days reduced first-order height error to a few centimeters.

A more comprehensive study and model development was conducted for the PARIS In-Orbit Demonstrator (PARIS-IOD) proposal (Martín-Neira et al., 2011). This was specified as a single-satellite demonstration of the GNSS altimetry concept, to validate hardware operations and error models, as a step toward an operational follow-on mission. With an emphasis on synoptic coverage of the ocean, this operational mission would improve revisit time by approximately a factor of 20 over a traditional nadir altimeter, with science requirements of 5 cm height error and 100 km along-track resolution. That study evaluated issues with the ionospheric delay error and the low bandwidth of the open GNSS signals on both frequencies. Combined, multi-frequency observations were required to remove a significant part of the ionospheric delay. Interferometric methods (iGNSS-R), in which the direct signal is used as a reference for cross-correlation with the reflected signal to utilize full signal bandwidth, were determined to be necessary to meet the science requirements. The PARIS-IOD design requires a pair of 23 dBi electronically steered antennas and the error budget was found to be 17 cm (including instrument, speckle, and ionosphere) from 800 km orbit but with along-track averaging of 100 km, which would have a significant impact on the spatial resolution. Ionospheric delay, proportional to $1/f^2$, remained a significant error, due to the comparably lower frequency of L-band.

GEROS-ISS (Wickert et al., 2016) was a more recent mission proposal for a technology demonstration on the International Space Station (ISS). With the exception of some complications for implementing precision orbit determination (POD) on a large, maneuvering platform in Low Earth Orbits (LEO), the design approach for GEROS-ISS follows that of PARIS-IOD with a high-gain steerable antenna. Speckle was predicted to account for less than 15 cm error in 100 km of averaging. Similarly, the GNSS Transpolar Earth Reflectometry exploriNg (G-TERN) mission was suggested for GNSS altimetry from polar orbit (ESA Earth Explorer 9, Revised Call). The altimetric performance expected at polar regions was better than 10 cm in cells of 30 km × 30 km every 3 days (0.5° × 0.5° in 10 days over the rest of the oceans) (Cardellach et al., 2018).

Summarizing, a large body of analysis, simulations, and experimentation have shown the feasibility of GNSS-R and its utility in providing improved spatial and temporal coverage at a significantly lower cost than conventional active radar nadir or wide-swath altimetry. These studies have also confirmed the three key limitations of the GNSS signal, each of which can be improved through application of similar methods to Ku-K band communication satellite transmissions: (1) Increasing the bandwidth from 10's of MHz in GNSS up to a maximum of 1 GHz in communication signals; (2) Increased EIRP due to the communication link budget requirement (50 dBW vs. 26 dBW); (3) Sensitivity to uncertainty in the ionospheric Total Electron Content (TEC) reduced to approximately 1–2% of that at L-band; and (4) Antenna dimensions reduced to approximately 9–13% of that at L-band (for center frequencies of 12–20 GHz) for the same gain.

Finally, although this section mainly covers the history on spaceborne GNSS-R for SSH measurement, it is worth noting that in past few years there has been some progress made on using ground based GNSS receivers to measure sea level (Larson et al., 2013, 2017). This technique uses existing network of geodetic GNSS antennas/receivers situated in view of the sea and receive the signal reflected by the sea (multipath) in the side lobes of the antenna. A recent 10-year comparison of water levels measured showed an RMS error of individual GPS water level estimates to be about 12 cm, with daily mean differences of about 2 cm with respect to conventional tide gauges (Larson et al., 2017). This is another promising method to measure coastal sea level (within a km from coast). This technique does, however, require the GPS stations to be properly sited near the shore and careful characterization of the study area for each of the station.

W-SoOp Overview – Theory and Algorithms

Modern digital satellite signals employ efficient compression and encryption, such that the transmitted signal can be approximated as a band-limited noise (Shah et al., 2012). Instruments designed to simultaneously measure these signals use similar interferometric techniques as those developed for GNSS-R, where the direct signal is used as a reference instead of a known pseudo-random noise (PRN) code. In this approach, existing wideband (~400–500 MHz to 1 GHz) digital transmissions from communication and broadcast satellite services are re-utilized as illumination sources in a bistatic radar system. There are a number of satellite transmitters that operate from C- to K-band, close to the frequencies used for radar altimetry, as shown in **Figure 9**. Global coverage of coastal areas is possible over a small period of time using a constellation of receivers, due to the presence of large number of transmitters (as shown in an example in **Figure 10**). A constellation using W-SoOp is feasible because this technique requires low-cost passive receivers with small antennas, developed from satellite communication heritage, which can be launched on SmallSat or CubeSat.

For W-SoOp measurement, simulations have shown that a 1–2 km spatial resolution is achievable from a space-based implementation using W-SoOp with 400–500 MHz bandwidth (Shah and Garrison, 2017). For altimetry measurement accuracy, a few cm in delay-precisions from coastal experiments was demonstrated using X-band digital TV signals (Ribó et al., 2014). Also, preliminary results from tower-based experiment that used both Ku and K-band transmissions from a commercial (DirecTV) direct broadcast satellite confirm the validity of the theoretical error model which predicts that the measurement precision from spaceborne receivers will be in the order of 5–6 cm (Shah and Garrison, 2017; Ho et al., 2019).

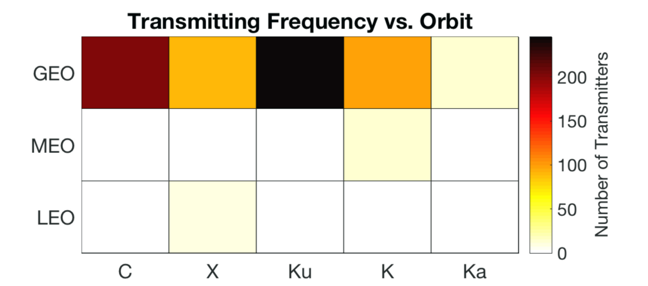

FIGURE 9 | Number of currently operational spaceborne transmitters between C- and Ka-band frequencies.

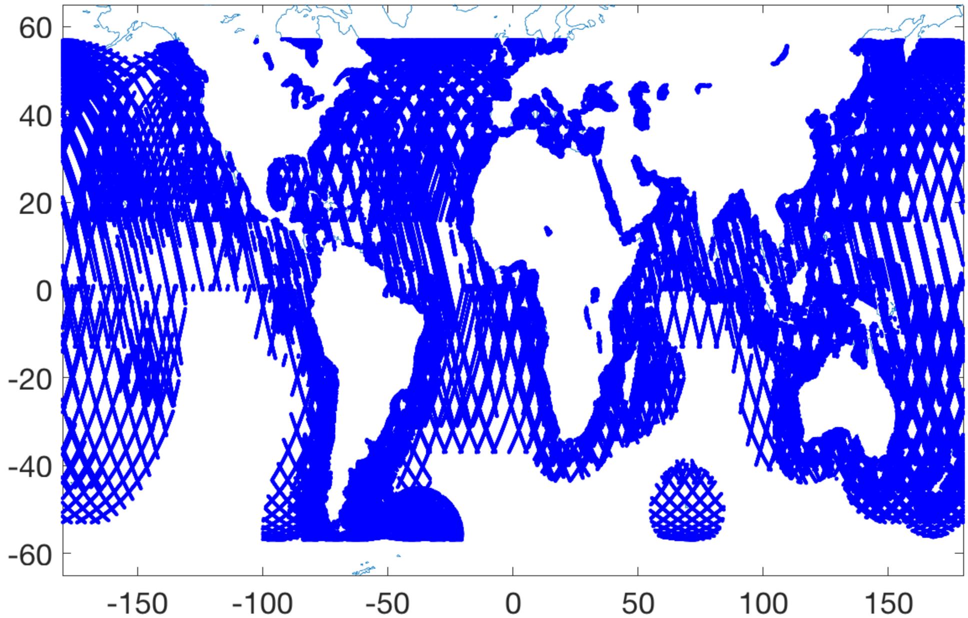

FIGURE 10 | Possible coverage of coastal areas from SoOp LEO satellites receiving commercial Ku-band transmitters. This figure shows the extent of the coverage in coastal regions.

Challenges of W-SoOp

Unlike dedicated remote sensing instruments, where all design parameters are traded off to maximize the performance of the instrument, the use of SoOp faces unavoidable design constraints derived from the properties of the transmitting systems that were originally intended for other purposes, and operated independently of any proposed science mission. As mentioned above, challenges for GNSS-R were linked to the weak and narrow-band transmitted signals. These problems are well solved when using communication and digital TV broadcasting satellites as SoOp. In the trade for SoOp reflectometry, however, other problems emerge, such as insufficiently precise knowledge of the transmitters' position, non-homogeneous coverage at the global (commercial operators will prefer to illuminate only densely inhabited areas, where their customers reside), the variable transmitted power for different transmitting channels, and the temporal variability of the allocation frequencies of a huge number of broadcast TV channels.

For coastal altimetry a major challenge is the estimation of the precise trajectory of the transmitting satellites. Although geosynchronous orbits are more predictable than LEO, the conventional positioning accuracy of the geostationary transmitters is in the range of few hundreds of meters (Rosengren et al., 2004; Guo et al., 2010). Frequent maneuvering of spacecraft and the limited public information available from the operators of these privately owned satellites adds even more uncertainty to estimates of their positioning. Several methods have been used or proposed in order to improve POD for geostationary orbits, including satellite laser ranging (SLR), the measurement of their angular position using ground-based telescopes (Montojo et al., 2011) and very-long-baseline interferometry (VLBI) delay and delay-rate tracking (Huang et al., 2011). Additional techniques, such as line-of-sight information from the LEO hosting a SoOp receiver and improved mathematical algorithms to numerically propagate orbit uncertainties still remain to be explored. An additional step forward in this direction is the incipient use of POD GNSS receivers aboard geosynchronous satellites. Although their use is mainly driven by their need during geosynchronous transfer orbits and electric thrusters (Marmet et al., 2015), next generation geosynchronous transmitters will also have POD (tens of meters). The most promising strategy will probably be a combination of several of these techniques to obtain POD of the GEOs that will enable altimetry with W-SoOp.

Commercial broadcast transmitters provide a large amount of transmitted TV channels, but they mainly transmit over densely populated areas. So, coverage with sufficient SNR over coastal areas is guaranteed, but not over open ocean. On the other hand, military transmitters with global coverage do exist (Kumar et al., 2005). These could be used to cover the illumination gap over open ocean if needed.

The periodic reallocation of TV channels at different frequency channels represents an additional logistic challenge for the instrument. Reprogramming capabilities of the receiver could easily solve the problem. In the long run, however, an intelligent instrument with decision making capabilities could increase the observational throughput.

Signal processing challenges are also envisaged, especially when the receiver has to cope with a large number of transmitters, channels, and polarizations within a very wide (1 GHz) bandwidth. Flexibility in the signal processing approach can be achieved with software defined radio (SDR) processors, although the current capacity of these technologies is limited to moderate bandwidths. A mixed processing solution based on SDR and highly efficient specialized hardware, as for instance hardware correlators or graphical processing units (GPU), may provide the necessary computational strength and flexibility at the same time. Finally, changes in the received power will have little effect in altimetric applications.

Scientific and Operational Applications

As mentioned above, in coastal oceans, small mesoscale eddies are energetic. As an example, **Figure 11** top left shows daily means SSH features in the Monterey Bay region produced by a regional model at a high resolution of 3 km. The model is driven by realistic hourly atmospheric forcing and tidal forcing. The region teems with energetic eddies of smaller than 100 km, and the eddies change within days. Traditional altimeters are incapable of capturing these features as they sample this area with only a few passes in a given 10-day period (**Figure 11**, top right). Even the forthcoming SWOT mission cannot reliably observe these features because of its repeat cycle of 21 days.

Sampling of the area at higher temporal and spatial resolution is possible by a constellation of satellites recording Ku-band SoOp. This is shown in **Figure 11** bottom left, where a coverage simulation was performed using 8 receivers in a 500 km orbit. The assumption is made that the receiver can pick any Ku-band signals and each receiver is capable of recording up to eight channels. It is observed that many distinct features can be observed from a constellation because of the dense spatial and temporal coverage. This is an improvement over the capabilities of existing orbital platforms.

Finally, the same coverage map is plotted against the known tsunamis on Pacific Ocean. **Figure 12** shows the sampling of the tsunamis using eight SoOp receivers operating in Ku-band. It can be seen that if we have a modest constellation of eight receivers, it would be capable of observing most of the near-shore tsunamis. The near-shore observation is important for early warnings to save lives.

Summary

SSH W-SoOp has the potential to provide higher temporal and spatial resolution measurements enabling coastal ocean

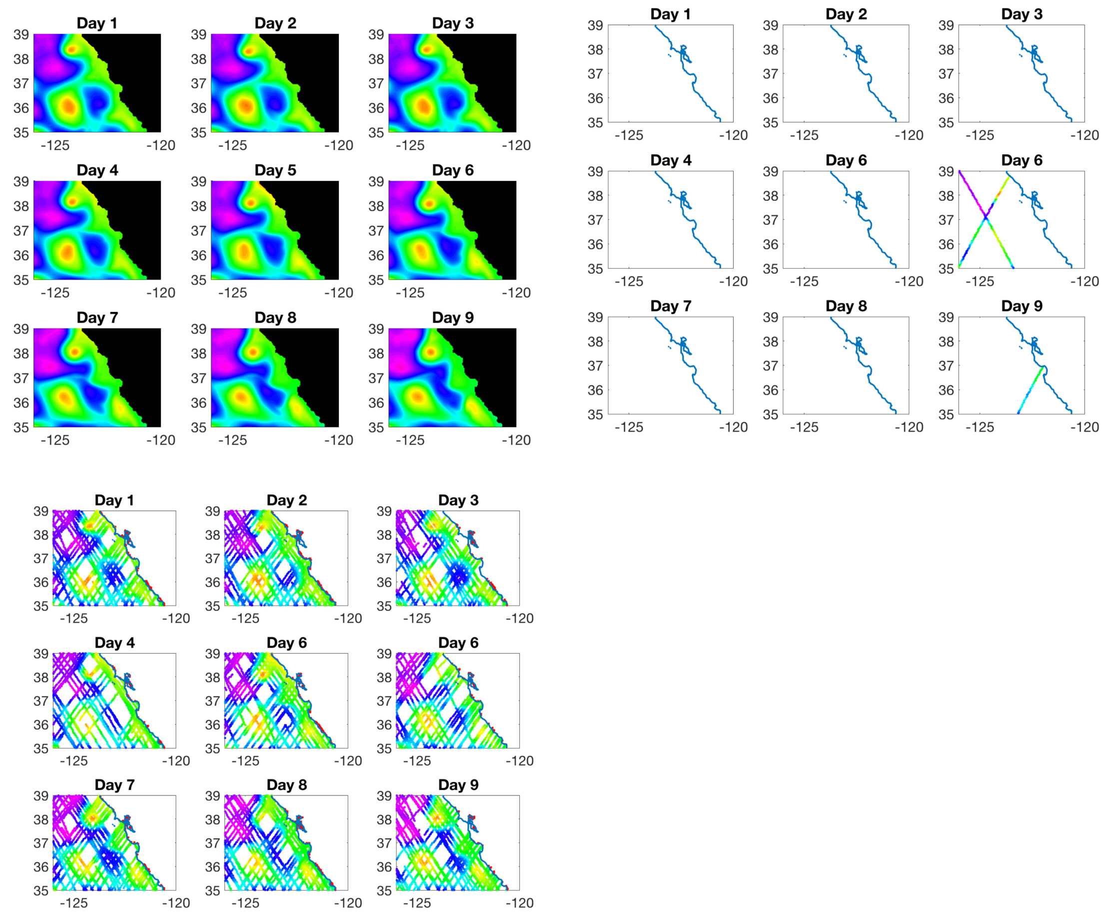

FIGURE 11 | The top left figure shows how the features of Monterey Bay changes spatially and temporally through a 9-day simulation. The top right figure shows sampling by traditional altimeters (Jason-3) of Monterey Bay area in 9-day period. The bottom left figure shows how the features of Monterey Bay can be sampled spatially and temporally using a constellation of eight receivers capable of capturing Ku-band reflected signals.

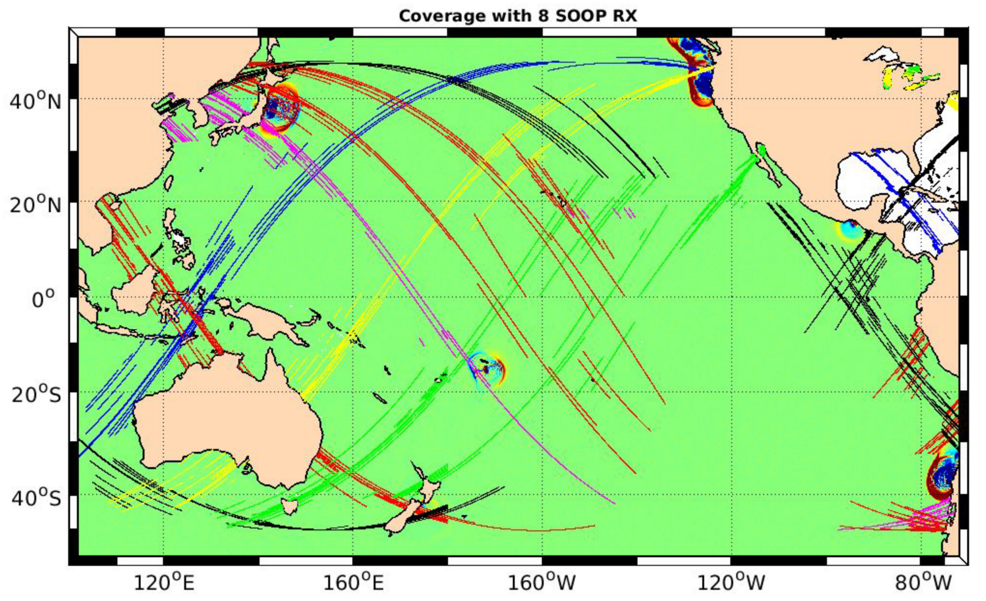

FIGURE 12 | Previously occurred tsunamis in the Pacific. Eight SoOp Receivers (different colors) are simulated.

circulation measurements down to sub-mesoscale. These measurements will improve our understanding of multi-scale circulations and thus of biological and chemical variability. In addition to the science values, the spatial and temporal coverage of SoOp for both ocean and land has unique operational values for coastal management. Coastal zones, currently home to a large fraction of the world's population, are under serious threat from sea level rise, coastal erosions, storm surges, and deadly tsunamis. As mentioned above, conventional satellite altimeters, as well as GNSS-R LEOs, have either too low temporal resolution or too weak SNR, which are inadequate for coastal applications. On the other hand, the W-SoOp has denser coverage in more populated areas; therefore, we believe the W-SoOp technology is ideal for coastal missions for both science and operational applications if the above-mentioned challenges can be resolved.

Roadmap and Recommendations for the Development of the SoOp Technique

The following steps need to be taken for the development of W-SoOp for coastal application measurements:

- *Study the impact of POD uncertainty in the final altimetric retrieval, investigate possible ways to improve POD.*
- *Study the receiving capabilities: how many transmitting satellites are visible simultaneously from a given LEO scenario? How different the properties of these signals are?*
- *Study solutions for the 2-polarization, multi-beam steering receiving antennas and receiving RF chains, generate a technology development roadmap leveraging recent advances in satellite communications to the greatest extent possible.*
- *Study solutions for flexible onboard processing.*
- *Define achievable science objectives and applications: With current technology and anticipated improvements in the next 5–10 years, what are the new science objectives and applications of SoOp, which could be achieved by other missions at the same cost.*

OPPORTUNITIES FOR INTEGRATION

As mentioned in section "Monitoring Coastal Zones With Multiple Observing Systems," the evolution of coastal zones results from several forcing factors (natural and anthropogenic). Assessing the impacts of present and future coastal evolution requires an understanding of the interactions between biophysical and socioeconomic systems and assets on land, and even in the adjacent sea. Looking at both land and sea, as well as natural and anthropogenic factors and related consequences, is the only way of pursuing the monitoring of such complex systems under various impacts (not only environmental). In addition, modeling and synthesis activities have to accompany the measurements so that the research can provide insight into the future evolution of coastal areas. To benefit a broad range of end users and a large variety of scientific and societal applications, a global database of various coastal products should be developed. International programs, e.g., in the context of Future Earth, could consider establishing a data repository gathering all needed coastal observations, whether collected locally or remotely.

Coastal altimetry is crucial for the coastal seas and is already enhancing the capabilities of coastal models to provide accurate physical parameters that can be integrated into biogeochemical applications of societal and economic importance. An example is

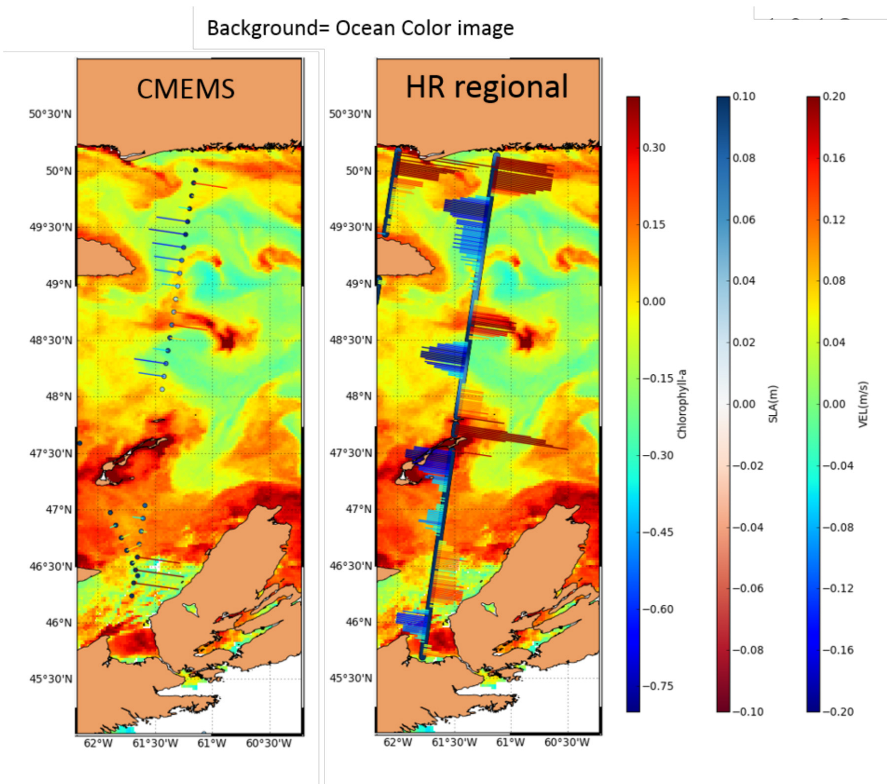

FIGURE 13 | Stick-plot of across-track geostrophic velocities in the Gulf of St Lawrence (Canada) computed from altimeter SLA of the CMEMS global altimetry dataset **(Left)** and of a regional high-resolution altimetry dataset **(Right)**. The background image deals with a high-resolution chlorophyll-*a* field produced by CLS processing chains for the same date on September 8, 2014. Copyright "Fisheries and Oceans Canada" and "Collecte Localisation Satellites."

how observed sea level falls due to El Niño impacted Indonesian corals (Ampou et al., 2017).

Data assimilation in coastal areas is currently not a routine practice. Recent advances in coastal ocean forecasting along the European Atlantic and Baltic coast arise from developments in numerical modeling, data assimilation and observational networks (Madsen et al., 2015; Stanev et al., 2016). The works combine observations and modeling and propose integrated coastal and regional ocean forecasting systems. Staneva et al. (2017) and Wiese et al. (2018) show the benefit of using atmospheric-wave regional coupled models when predicting extreme events. Comparison between model and Jason-2, SARAL/AltiKa and CryoSat-2 altimeter observations indicate that the two-way coupling improves the simulation of wind and wave parameters of the model (Wahle et al., 2017). Moreover, the quality of the Sentinel-3A SWH over coastal zone is found superior to previous altimeter data (Wiese et al., 2018).

Improving our understanding of coastal ocean processes requires multi-platform approaches combining innovative and traditional observing systems (both *in situ* and satellite) with high resolution numerical simulations (Kourafalou et al., 2015). During the last decade, progress has been made, for example in the Mediterranean Sea, a natural reduced-scale laboratory for the examination of processes of global importance with multiple interacting scales including shelf-slope exchanges.

Encouraging results concerning the use of autonomous underwater vehicles (gliders) in synergy with altimetry, in order to monitor dynamics in the Balearic Sea, have been obtained (Ruiz et al., 2009). Bouffard et al. (2010) developed innovative strategies to characterize horizontal ocean flows, specifically in terms of current velocity associated with filaments, eddies or shelf-slope flow modifications close to the coast. These methodologies were applied to a series of glider missions carried out almost simultaneously and co-localized along the altimeter tracks. The value added by combining remote and *in situ* sensors to validate, inter-calibrate, and improve observing data dedicated to coastal ocean studies has been shown (Pascual et al., 2013). For instance, high-resolution hydrographic fields from gliders revealed the presence relatively intense eddies, that were not correctly detected by standard altimeter fields. In this context, Escudier et al. (2013) proposed a two-step optimal interpolation scheme including a bathymetric constraint with the aim of improving the characterization of coastal and fine-scale features. Qualitative and quantitative comparisons with drifters, glider, and satellite sea surface temperature observations reveal that when the new altimetry products are used, a better agreement is obtained.

Another example is the integration of altimeter data in the coastal band (7–60 km from the seashore) together with measurements of the surface velocity from coastal High Frequency Radars that provide synoptic, high frequency and high-resolution data at the boundary between the ocean and the atmosphere. Troupin et al. (2015) shows clear evidence during a glider mission conducted along a track from the Franco-Indian SARAL/AltiKa altimeter (Verron et al., 2015) located in the Western Mediterranean close to Ibiza Island, where the SOCIB HF radar facility provided hourly surface current velocities. Surface drifters were also deployed in the studied region. Comparisons reveal a reasonable agreement between all platforms (drifter, SARAL/AltiKa, glider, and HF radar), with SARAL/AltiKa able to capture the northern edge of a meander, which lied on a shallow bathymetry less than 10 km from the coast. Pascual et al. (2015) and Verron et al. (2018) show that SARAL/AltiKa data can be retrieved at a distance of only 7 km from the coast. The derived velocities reveal coherent mesoscale features with high temporal variability among the different cycles and with general reasonable agreement with HF radar fields.

New generations of SAR altimeter missions have demonstrated that compared to conventional altimetry (or low-resolution mode), this technique significantly reduces the measurements level of noise and improves the along-track spatial resolution (Boy et al., 2017). The comparison between altimetry, ocean gliders and ADCP showed a significant improvement, order 30% in resolution and 42% in velocity accuracy using a synthetic aperture radar mode with respect to lower-resolution mode of conventional altimetry (Heslop et al., 2017). Integrating the three datasets provided valuable insight into the variability of oceanographic features, in an area of the Mediterranean that remains chronically under sampled and has demonstrated benefits to improve knowledge on coastal and fine-scale dynamics.

Future works will require expanded observing capabilities with new high-resolution experiments integrating multiplatform approaches with numerical simulations (see an example in Pascual et al., 2017 pointing to the predominance of fine-scale processes enhancing vertical exchanges between the upper ocean and the ocean interior). Particular emphasis will be devoted to the calibration and validation of the wide-swath SWOT altimeter, that will make an unprecedented contribution by enabling the first observations in the 40–100 km wavelength band (Gómez-Navarro et al., 2018).

The availability of processing platforms, such as the European Space Agency G-POD online service called SARvatore (SAR Versatile Altimetric Toolkit for Ocean Research and Exploitation) will further support the advanced exploitation of coastal altimetry data sets (Dinardo, 2014). Moreover, it is expected that new thematic processing platforms will permit integrating coastal altimetry with data from multiple sources (Clerc et al., 2016) enabling new opportunities to understand important ocean processes in the coastal zone that traditionally require sampling at appropriate temporal, spatial, and depths scales. Sustained funding mechanisms are essential to bring together end-user/modelers and coastal altimetry producers in order to go further in the integration.

W-SoOp is an emerging technology, which has potential to provide sub-diurnal temporal resolution through use of constellations. Because of the increased temporal resolution, this technique would be very complimentary to the existing as well as upcoming measurement in coastal zone in understanding short duration variation in ocean processes in coastal zone. However, before studies on integration with the existing observations are thoroughly explored, more work is needed in the technology development as elaborated in roadmap section in Section "Wideband Signals of Opportunity Reflectometry for Coastal Ocean Applications."

END USERS ENGAGEMENT

Collecting information about coastal zones and their evolution has obvious societal interest. In addition to the science needed to increase knowledge about the processes that affect the coastal areas and about the complex changes these regions suffer, (e.g., in the context of international programs such as WCRP or Future Earth), a number of other stakeholders will benefit of multi-source, multi parameters information about coastal zones.

Although each country is organized differently, the management of coastal risks always includes users concerned with:

- The prevention of coastal hazards and adaptation to climate change, which generally involves ***private and public stakeholders such as coastal municipalities and economic stakeholders***, within a process that can be part of a national or regional regulation or may follow sectoral guidance. For these stakeholders, the observational priority is to collect information allowing to assess present-days and future coastal hazards such as shoreline changes and flooding.
- Crisis management and preparedness, where the priorities is generally to save lives and where near real time services need to be set up, in order to inform the ***civil security*** or similar organization and organize the rescue appropriately. For example, the Copernicus Emergency Management system addresses this need by providing a service for rapid hazard mapping[2].
- Post-disaster reconstruction, involving ***private and public stakeholders as well as the finance, insurance and reinsurance industries***, during which coastal observations are required to assess future coastal risks in order to increase resilience and favor adaptation to climate change. In addition to these three traditional groups of users in the area of coastal risk management, a growing number of users is concerned with present-days climate change impacts (detection and attribution, e.g., Le Cozannet et al., 2014), its future impacts, and methods to evaluate the efficiency of adaptation strategies (Hallegatte, 2009). This usually include national to regional authorities and agencies in charge of developing adaptation strategies

[2]http://emergency.copernicus.eu/

(Le Cozannet et al., 2017). To give an example, studies quantifying shoreline changes based on high-resolution imagery in atoll islands have allowed reconsidering adaptation priorities. Hence, the traditional debate focused on land losses has now shifted to a more integrated assessment of islands habitability, considering chronic and extreme flooding as well as the impacts of climate change on corals and water resources (Nurse et al., 2014). However, as the methods allowing maximizing the efficiency of adaptation are not well established yet, there are still research needs to assess how observations can best support adaptation.

In addition, in order to exploit the economic investments in space-based observing systems, the development of operational services based on EO data is a key goal. The operational services (downstream services) are based on the integration of multi-source information (EO, modeling, and *in situ*) with the institutional/policy, social and economic knowledge. The sustainability of these operational services can be guaranteed by their usefulness and thus their capacity to fulfill coastal user (intermediate and final) needs (Taramelli et al., 2014, 2015a,b).

Several coastal altimetry experiments showed that applying locally all the altimeter processing steps up to sea level anomalies at high-resolution is an efficient way to get a more accurate estimation of the coastal dynamics. In fact, outside the last tenth kilometers near the coast, ocean retracking algorithms perform well and a dedicated high-resolution processing, particularly data selection and noise reduction, enables to monitor small-scale patterns with more details, which is relevant for regional oceanographers. **Figure 13** shows across-track geostrophic velocities computed from altimetric SLA in the Gulf of St Laurence (Canada) from the global (from Copernicus Marine Environment Monitoring Service, CMEMS) and regional high-resolution datasets. The statistical comparison of along-track altimeter to *in situ* sea level observation at three coastal tide gauges, gives better results with the HR regional product in term of correlation (between 0.6 and 0.9 depending on the altimeter point) and similar results in term of RMS of the difference (<0.06 m). This confirms that the good quality of the CMEMS altimeter data is maintained in the HR regional product.

In terms of communication and capacity building, the Coastal Altimetry Workshop series organized for more than 10 years by ESA (Restano et al., 2018) have already attracted the regional ocean modeling community as end-users. A significant need has been expressed for continuous education of the user community on the data products and updates, as it is a daunting task for a user to determine which dataset to use. This objective can be achieved augmenting information for non-expert altimetrists and coastal oceanography users with, for example, clear statements of the time range of data availability for single altimeter platform data sets, and notes of proximity to the coast of valid data. Model users have also requested global unified multi-platform high along-track resolution products, such as what the TAPAS initiative (Tailored Altimeter Products for Assimilation Systems) is delivering for European seas. The TAPAS working group set up within CMEMS is a very good example of the way to proceed to engage end-users by establishing a strong link between Data Assimilation teams and Sea Level production center. Both communities are strengthened by the exchanges and more efficient research and development driven by data usage. A similar initiative called ARCOM for Altimetry for Regional and Coastal models was proposed in 2015 for extending the TAPAS experience to a larger community, targeting the GODAE OceanView Coastal and Shelf Seas Task Team (COSS-TT) group. A pilot workshop was conducted in 2015 in association with a COSS-TT international coordination meeting. The Coastal Altimetry community brought tutorials about altimetry processing and products to coastal modelers in order to feed discussions on the main issues (reference surfaces, geophysical corrections, observation errors). In 2017, a dedicated session was re-conducted in the COSS-TT meeting. The outcome of this last ARCOM event was a claim for more details to help making a choice between the available datasets (coverage in time and spatial, strength, etc.).

An example of end-user engagement is the ESA eSurge-Venice project that brought together research institutes and stakeholders (sea level forecast center of the Venice Municipality) and that has been set up to help improve the modeling of storm surges around city of Venice using coastal altimetry and scatterometry (De Biasio et al., 2017). The city of Venice is one example of worldwide places that are vulnerable to storm surges, being the city flooded several times a year. A barrier system, MOSE, is being operated to protect the city, however, for the opening/closure of the barrier accurate predictions of sea level is essential.

As for the W-SoOp technique, the technology is still in early days and the concept is still trying to carve out the best way to go get end-user engaged. Some of the modelers have recently started looking at OSSE studies to explore the potentials.

CONCLUSIONS

To understand the complexity of coastal zones and their evolution under multiple forcing processes, a broad variety of observations needs to be made with a long-term sustained perspective, and as global as possible coverage. This implies considerable investments in both space-based and *in situ* observing systems. In this paper, we have identified a number of parameters, which are require to be systematically monitored to improve knowledge on the forcing agents and the morphological changes of the shorelines in response to imposed forcing.

This paper recognizes the prominent role of local to regional coastal observatories in collecting, analyzing, and disseminating information derived from satellite, aerial and *in situ* coastal observations. This applies in the area of coastal sea-levels and related hazards (shoreline changes and flooding), as discussed in this paper, but also beyond that in the area of coastal environment and biodiversity monitoring (see e.g., Liu et al., 2015). We argue that a timely challenge for increasing the salience of coastal information is to connect global providers of EO data (such as space agencies) with the emerging networks of coastal observatories. In other fields of geosciences, several previous initiatives have efficiently established such links and stimulated the use of satellite-based observations in scientific and operational activities. This is the case for the ESA "supersites" or NASA "natural laboratories," providing access to all geophysical data for key priority sites affected by earthquakes and volcanic eruptions. This could be an example to follow for coastal zone evolution.

Among the forcing agents, we have focused on coastal sea level monitoring by satellite altimetry in this paper. The spatial and temporal complexity of coastal sea level requires a fine-scale monitoring. Satellite altimetry is capable of providing a unique and global long-term observational dataset to characterize how sea level variability evolves from the open ocean to the coastal zone. It can help to fill the gap between open ocean and tide gauges. The extension of the satellite-based sea level record toward the coast with quality comparable to open ocean is a key requirement for a proper understanding of the variability of sea level at all temporal and spatial scales. Conventional altimetry fails to provide sea level data within 10 km from the coast. But efforts performed during the past decade by the international coastal altimetry community with support of space agencies, in particular ESA, have clearly demonstrated that retracking of radar echoes collected by the satellite as it approaches the coast and computation of new geophysical corrections optimized for the coastal areas (e.g., WTC, atmospheric loading, sea state bias, ocean tides) allow rescue of sea level data in this 10-km gap.

As discussed in Section "Coastal Zone Altimetry Processing and Exploitation: Progress and Outlook for the Next Decade," detailed studies have been conducted in several pilot regions, showing that sea surface height data can be recovered with an improved precision near the coast, with the goal to reach the accuracy in open ocean. Studies have also shown that use of SAR/DDA data from the Sentinel-3 and CryoSat missions can provide even higher performances in coastal areas, both in terms of precision, 3–4 cm as close as 2–3 km to the coast (Dinardo et al., 2017), and resolution (up to 300 m to the coast – this can be improved by processing the data at the burst frequency, 80 Hz, 90 m, and further improved with the fully focused SAR processing). For scientific and societal applications, the next step is now to undertake systematic exploitation of altimetry-based data in order to deliver worldwide coastal sea level products, easily usable by a broad variety of end users. There is strong demand for such information from both the scientific community and other stakeholders.

On a longer perspective, we have also discussed promising new technology based on W-SoOp reflectometry to complement the information provided by satellite altimetry on sea level in the coastal zone. This technique can potentially get closer to the coast than conventional altimetry and with the use of constellation provide data at higher temporal resolution that can be used to study the dynamic coastal zone. The next step on this technique is to study the impact of POD uncertainty in the final altimetric retrieval, as this is currently the limiting error source for this technique. Additionally, in parallel, it is important to work with the scientific community to understand how these measurements can improve our understanding on coastal processes through OSSE studies.

AUTHOR CONTRIBUTIONS

JBe assembled the manuscript. AC, SV, LF-M, and RSh wrote and edited most sections of the manuscript, other authors also wrote specific parts of the document. All authors contributed to manuscript revision, read and approved the submitted version.

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REFERENCES

Ablain, M., Legeais, J. F., Prandi, P., Marcos, M., Fenoglio-Marc, L., Benveniste, J., et al. (2016). Satellite altimetry-based sea level at global and regional scales. *Surv. Geophys.* 38, 7–31. doi: 10.1007/s10712-016-9389-8

Abulaitijiang, A., Andersen, O. B., and Stenseng, L. (2015). Coastal sea level from inland CryoSat-2 interferometric SAR altimetry. *Geophys. Res. Lett.* 42, 1841–1847. doi: 10.1002/2015GL063131

Ampou, E. E., Johan, O., Menkes, C. E., Niño, F., Birol, F., Ouillon, S., et al. (2017). Coral mortality induced by the 2015–2016 El-Niño in Indonesia: the effect of rapid sea level fall. *Biogeosciences* 14, 817–826. doi: 10.5194/bg-14-817-2017

Antony, C., Testut, L., and Unnikrishnan, A. S. (2014). Observing storm surges in the Bay of Bengal from satellite altimetry. *Estuar. Coast. Shelf Sci.* 151, 131–140. doi: 10.1016/j.ecss.2014.09.012

Arns, A., Dangendorf, S., Jensen, J., Talke, S., Bender, J., and Pattiaratchi, C. (2017). Sea-level rise induced amplification of coastal protection design heights. *Sci. Rep.* 7:40171. doi: 10.1038/srep40171

Bajo, M., De Biasio, F., Umgiesser, G., Vignudelli, S., and Zecchetto, S. (2017). Impact of using scatterometer and altimeter data on storm surge forecasting. *Ocean Model.* 113, 85–94. doi: 10.1016/j.ocemod.2017.03.014

Bird, E. C. F. (1985). Coastline changes: a global review. *Geol. J.* 152:108. doi: 10.1002/gj.3350210215

Birol, F., and Delebecque, C. (2014). Using high sampling rate (10/20 Hz) altimeter data for the observation of coastal surface currents: a case study over the northwestern Mediterranean Sea. *J. Mar. Syst.* 129, 318–333. doi: 10.1016/j.jmarsys.2013.07.009

Birol, F., Fuller, N. X., Lyard, F., Cancet, M., Niño, F., and Delebecque, C. (2017). Coastal applications from nadir altimetry: example of the X-TRACK regional products. *Adv. Space Res.* 59, 936–953. doi: 10.1016/j.asr.2016.11.005

Bonnefond, P., Laurain, O., Exertier, P., Boy, F., Guinle, T., Picot, N., et al. (2018a). Calibrating the SAR SSH of sentinel-3A and CryoSat-2 over the Corsica facilities. *Remote Sens.* 10:92. doi: 10.3390/rs10010092

Bonnefond, P., Verron, J., Aublanc, J., Babu, K. N., Bergé-Nguyen, M., Cancet, M., et al. (2018b). The benefits of the Ka-band as evidenced from the SARAL/AltiKa Altimetric mission: quality assessment and specificities of AltiKa data. *Remote Sens.* 10:83. doi: 10.3390/rs10010083

Bouffard, J., Naeije, M., Banks, C. J., Calafat, F. M., Cipollini, P., Snaith, H. M., et al. (2018). CryoSat ocean product quality status and future evolution. *Adv. Space Res.* 62, 1549–1563. doi: 10.1016/j.asr.2017.11.043

Bouffard, J., Pascual, A., Ruiz, S., Faugère, Y., and Tintoré, J. (2010). Coastal and mesoscale dynamics characterization using altimetry and gliders: a case study in the Balearic Sea. *J. Geophys. Res. Oceans* 115:C10029. doi: 10.1029/2009JC006087

Boy, F., Desjonquères, J.-D., Picot, N., Moreau, T., and Raynalm, M. (2017). CryoSat-2 SAR-mode over oceans: processing methods, global assessment, and benefits. *IEEE Trans. Geosci. Remote Sens.* 55, 148–158. doi: 10.1109/TGRS.2016.2601958

Brooks, B. A., Merrifield, M. A., Foster, J., Werner, C. L., Gomez, F., Bevis, M., et al. (2007). Space geodetic determination of spatial variability in relative sea level change, Los Angeles basin. *Geophys. Res. Lett.* 34:L01611. doi: 10.1029/2006GL028171

Brown, S. (2010). A novel near-land radiometer wet path-delay retrieval algorithm: application to the Jason-2/OSTM advanced microwave radiometer. *IEEE Trans. Geosci. Remote Sens.* 48, 1986–1992. doi: 10.1109/TGRS.2009.2037220

Buchhaupt, C., Fenoglio-Marc, L., Dinardo, S., Scharroo, R., and Becker, M. (2017). A fast convolution based waveform model for conventional and unfocused SAR altimetry. *Adv. Space Res.* 62, 1445–1463. doi: 10.1016/j.asr.2017.11.039

Cardellach, E., Wickert, J., Baggen, R., Benito, J., Camps, A., Catarino, N., et al. (2018). GNSS transpolar earth reflectometry exploriNg system (G-TERN): mission concept. *IEEE Access* 6, 13980–14018. doi: 10.1109/ACCESS.2018.2814072

Carrère, L., Lyard, F., Cancet, M., Guillot, A., and Picot, N. (2014). "FES 2014, a new tidal model - Validation results and perspectives for improvements," in *Proceedings of the ESA Living Planet Conference, 9–13 May 2016, ESA*, Vol. 740, Prague.

Cazenave, A., and Le Cozannet, G. (2014). Sea level rise and its coastal impacts. *Earths Future* 2, 15–34. doi: 10.1002/2013EF000188

Cazenave, A., Le Cozannet, G., Benveniste, J., Woodworth, P., and Champollion, N. (2017). Monitoring the change of coastal zones from space. *EOS* 98. doi: 10.1029/2017EO085581

Cazenave, A., Palanisamy, H., and Ablain, M. (2018). Contemporary sea level changes from satellite altimetry: what have we learned? What are the new challenges? *Adv. Space Res.* 62, 1639–1653. doi: 10.1016/j.asr.2018.07.017

Chelton, D. B., Schlax, M. G., Samelson, R. M., and de Szoeke, R. A. (2007). Global observations of large oceanic eddies. *Geophys. Res. Lett.* 34:L15606. doi: 10.1029/2007GL030812

Chen, N., Han, G., Yang, J., and Chen, D. (2014). Hurricane Sandy storm surge observed by HY- 2A satellite altimetry and tide gauges. *J. Geophys. Res. Oceans* 119, 4542–4548. doi: 10.1002/2013JC009782

Cipollini, P., Benveniste, J., Birol, F., Fernandes, M. J., Obligis, E., Passaro, M., et al. (2017). "Satellite altimetry in coastal regions," in *Satellite Altimetry Over Oceans and Land Surfaces Earth Observation of Global Changes Book Series*, eds D. Stammer and A. Cazenave (London: CRC Press), 644.

Clerc, S., Tuhoy, E., Mangin, A., Datcu, M., Vignudelli, S., Illuzzi, D., et al. (2016). New perspectives for the observation of coastal zones with the coastal thematic exploitation platform. *Proc. Living Planet Symp.* 740:27.

Crétaux, J.-F., Nielsen, K., Frappart, F., Papa, F., Calmant, S., and Benveniste, J. (2018). "Hydrological applications of satellite altimetry: rivers, lakes, man-made reservoirs, inundated areas," in *Satellite Altimetry Over Oceans and Land Surfaces, Earth Observation of Global Changes*, eds D. Stammer and A. Cazenave (Boca Raton, FL: CRC Press), 459–504. doi: 10.1201/9781315151779-14

Cullen, R. A., and Wingham, D. J. (2002). "CryoSat level 1b processing algorithms and simulation results," in *Proceeding of Geoscience and Remote Sensing Symposium (IGARSS)*, Toronto. doi: 10.1109/IGARSS.2002.1026246

De Biasio, F., Bajo, M., Vignudelli, S., Umgiesser, G., and Zecchetto, S. (2017). Improvements of storm surge forecasting in the Gulf of Venice exploiting the potential of satellite data: the ESA DUE eSurge-Venice project. *Eur. J. Remote Sens.* 50, 428–441. doi: 10.1080/22797254.2017.1350558

De Biasio, F., Vignudelli, S., Della Valle, A., Umgiesser, G., Bajo, M., and Zecchetto, S. (2016). Exploiting the potential of satellite microwave remote sensing to hindcast the storm surge in the gulf of Venice. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* 9, 5089–5105. doi: 10.1109/JSTARS.2016.2603235

Deng, X., and Featherstone, W. E. (2006). A coastal retracking system for satellite radar altimeter waveforms: application to ERS-2 around Australia. *J. Geophys. Res. Oceans* 111:C06012. doi: 10.1029/2005JC003039

Desportes, C., Obligis, E., and Eymard, L. (2007). On the wet tropospheric correction for altimetry in coastal regions. *IEEE Trans. Geosci. Remote Sens.* 45, 2139–2149. doi: 10.1109/TGRS.2006.888967

Dinardo, S. (2014). *GPOD CryoSat-2 SARvatore Software Prototype User Manual*. Available at: https://wiki.services.eoportal.org/tiki-index.php?page=GPOD+CryoSat-2+SARvatore+Software+Prototype+User+Manual (accessed 23 February 2018).

Dinardo, S., Fenoglio-Marc, L., Buchhaupt, C., Becker, M., Scharro, R., Fernandez, J., et al. (2017). Coastal SAR and PLRM altimetry in German bight and west Baltic sea. *Adv. Space Res.* 62, 1371–1404. doi: 10.1016/j.asr.2017.12.018

Dong, C., Xu, G., Han, G., Chen, N., He, Y., and Chen, D. (2018). Identification of tidal mixing fronts from high-resolution along-track altimetry data. *Remote Sens. Environ.* 209, 489–496. doi: 10.1016/j.rse.2018.02.047

Egido, A., and Smith, W. (2017). Fully focused SAR altimetry: 'theory and applications. *IEEE Trans. Geosci. Remote Sens.* 55, 392–406. doi: 10.1109/TGRS.2016.2607122

Escudier, R., Bouffard, J., Pascual, A., Poulain, P. M., and Pujol, M. I. (2013). Improvement of coastal and mesoscale observation from space: application to the northwestern Mediterranean Sea. *Geophys. Res. Lett.* 40, 2148–2153. doi: 10.1002/grl.50324

Eurosion (2004). www.eurosion.org (accessed June 20, 2019).

Fenoglio, L., Dinardo, S., Buchhaupt, C., Uebbing, B., Scharroo, R., Kusche, J., et al. (2019). "Calibrating CryoSat-2 and Sentinel-3A sea surface heights along the German coast," *IAG Proceedings*, Springer Verlag. doi: 10.1007/1345_2019_73

Fenoglio-Marc, L., Dinardo, S., Scharroo, R., Roland, A., Dutour, M., Lucas, B., et al. (2015a). The German bight: a validation of CryoSat-2 altimeter data in SAR mode. *Adv. Space Res.* 55, 2641–2656. doi: 10.1016/j.asr.2015.02.014

Fenoglio-Marc, L., Scharroo, R., Annunziato, A., Mendoza, L., Becker, M., and Lillibridge, J. (2015b). Cyclone Xaver seen by geodetic observations. *Geophys. Res. Lett.* 42, 9925–9932. doi: 10.1002/2015GL065989

Fernandes, M. J., and Lázaro, C. (2016). GPD+ wet tropospheric corrections for CryoSat-2 and GFO altimetry missions. *Remote Sens.* 8:851. doi: 10.3390/rs8100851

Fernandes, M. J., and Lázaro, C. (2018). Independent assessment of sentinel-3A wet tropospheric correction over the open and coastal ocean. *Remote Sens.* 10:484. doi: 10.3390/rs10030484

Fernandes, M. J., Lázaro, C., Ablain, M., and Pires, N. (2015). Improved wet path delays for all ESA and reference altimetric missions. *Remote Sens. Environ.* 169, 50–74. doi: 10.1016/j.rse.2015.07.023

Fernandes, M. J., Lazaro, C., Nunes, A. L., Pires, N., Bastos, L., and Mendes, V. B. (2010). GNSS-derived path delay: an approach to compute the wet tropospheric correction for coastal altimetry. *IEEE Geosci. Remote Sens. Lett.* 7, 596–600. doi: 10.1109/LGRS.2010.2042425

Fernandes, M. J., Lázaro, C., Nunes, A. L., and Scharroo, R. (2014). Atmospheric corrections for altimetry studies over inland water. *Remote Sens.* 6, 4952–4997. doi: 10.3390/rs6064952

Fernandes, M. J., Pires, N., Lázaro, C., and Nunes, A. L. (2013). Tropospheric delays from GNSS for application in coastal altimetry. *Adv. Space Res.* 51, 1352–1368. doi: 10.1016/j.asr.2012.04.025

Garrison, J. L., Komjathy, A., Zavorotny, V. U., and Katzberg, S. J. (2002). Wind speed measurement using forward scattered GPS signals. *IEEE Trans. Geosci. Remote Sens.* 40, 50–65. doi: 10.1109/36.981349

Gómez-Enri, J., Cipollini, P., Passaro, M., Vignudelli, S., Tejedor, B., and Coca, J. (2016). Coastal altimetry products in the strait of Gibraltar. *IEEE Trans. Geosci. Remote Sens.* 54, 5455–5466. doi: 10.1109/TGRS.2016.2565472

Gómez-Enri, J., Vignudelli, S., Cipollini, P., Coca, J., and González, C. J. (2017). Validation of CryoSat-2 SIRAL sea level data in the eastern continental shelf of the Gulf of Cadiz (Spain). *Adv. Space Res.* 62, 1405–1420. doi: 10.1016/j.asr.2017.10.042

Gómez-Navarro, L., Fablet, R., Mason, E., Pascual, A., Mourre, B., Cosme, E., et al. (2018). SWOT spatial scales in the western Mediterranean sea derived from pseudo-observations and an Ad Hoc filtering. *Remote Sens.* 10:599. doi: 10.3390/rs10040599

Guo, R., Hu, X., Tang, B., Huang, Y., Liu, L., Cheng, L., et al. (2010). Precise orbit determination for geostationary satellites with multiple tracking techniques. *Chin. Sci. Bull.* 55, 687–692. doi: 10.1007/s11434-010-0074-x

Hajj, G. A., and Zuffada, C. (2003). Theoretical description of a bistatic system for ocean altimetry using the GPS signal. *Radio Sci.* 38, 10–11. doi: 10.1029/2002RS002787

Hallegatte, S. (2009). Strategies to adapt to an uncertain climate change. *Glob. Environ. Change* 19, 240–247. doi: 10.1016/j.gloenvcha.2008.12.003

Han, G. (2017). "Altimeter surveys, coastal tides, and shelf circulation," in *Encyclopedia of Coastal Science*, eds C. W. Finkl and C. Makowski (Berlin: Springer Science & Business Media). doi: 10.1007/978-3-319-48657-4_7-2

Han, G., Ma, Z., Chen, D., and Chen, N. (2012). Observing storm surges from space: hurricane Igor off Newfoundland. *Sci. Rep.* 2:1010. doi: 10.1038/srep01010

Han, G., Ma, Z., Chen, N., Chen, N., and Yang, J. (2017). Hurricane Isaac storm surges off Florida observed by Jason-1 and Jason-2 satellite altimeters. *Remote Sens. Environ.* 198, 244–253. doi: 10.1016/j.rse.2017.06.005

Heslop, E. E., Saìnchez-Romaìn, A., Pascual, A., Rodrìguez, D., Reeve, K. A., FaugeÌre, Y., et al. (2017). Sentinel-3A views ocean variability more accurately at finer resolution. *Geophys. Res. Lett.* 44, 12367–12374. doi: 10.1002/2017GL076244

Ho, S. C., Shah, R., Garrison, J. L., Mohammad, P. N., Scheonwald, A., Pannu, R., et al. (2019). Wideband ocean altimetry using Ku-band and K-band satellite signals of opportunity: proof of concept. *IEEE Geosci. Remote Sens. Lett.* 16, 1012–1016. doi: 10.1109/LGRS.2019.2891976

Huang, Y., Hu, X., Zhang, X., Jiang, D., Guo, R., Wang, H., et al. (2011). Improvement of orbit determination for geostationary satellites with VLBI tracking. *Chin. Sci. Bull.* 56, 2765–2772. doi: 10.3390/s130302911

Idžanović, M., Ophaug, V., and Andersen, O. B. (2017). Coastal sea level from CryoSat-2 SARIn altimetry in Norway. *Adv. Space Res.* 62, 1344–1357. doi: 10.1016/j.asr.2017.07.043

IOC (2012). *Global Sea Level Observing System (GLOSS) Implementation Plan – 2012. UNESCO/IOC, IOC Technical Series No. 100. GOOS Report No. 194, JCOMM Technical Report No. 66*, 41. Available at: http://unesdoc.unesco.org/images/0021/002178/217832e.pdf (accessed June 20, 2019).

Jebri, F., Birol, F., Zakardjian, B., Bouffard, J., and Sammari, C. (2016). Exploiting coastal altimetry to improve the surface circulation scheme over the central Mediterranean Sea. *J. Geophys. Res. Oceans* 121, 4888–4909. doi: 10.1002/2016jc011961

Kourafalou, V. H., De Mey, P., Le Hénaff, M., Charria, G., Edwards, C. A., He, R., et al. (2015). Coastal Ocean Forecasting: system integration and evaluation. *J. Operat. Oceanogr.* 8, s127–s146. doi: 10.1080/1755876X.2015.1022336

Kumar, R., Taggart, D., Monzingo, R., and Goo, G. (2005). "Wideband gapfiller satellite (WGS) system," in *Proceedings of the 2005 IEEE Aerospace Conference*, (Big Sky, MT: IEEE), 1410–1417.

Larson, K. M., Ray, R. D., Nievinski, F. G., and Freymueller, J. T. (2013). The accidental tide gauge: a GPS reflection case study from Kachemak Bay, Alaska. *IEEE Geosci. Remote Sensing Lett.* 10, 1200–1204. doi: 10.1109/LGRS.2012.2236075

Larson, K. M., Ray, R. D., and Williams, S. D. P. (2017). A 10-year comparison of water levels measured with a geodetic GPS receiver versus a conventional tide gauge. *J. Atmos. Ocean Technol.* 34, 295–307. doi: 10.1175/JTECH-D-16-0101.1

Le Cozannet, G., Daniel, R., Guy, W., Manuel, G., Sylvestre, D. S., Benoit, M., et al. (2015). Vertical ground motion and historical sea-level records in Dakar (Senegal). *Environ. Res. Lett.* 10:084016. doi: 10.1088/1748-9326/10/8/084016

Le Cozannet, G., Garcin, M., Yates, M., Idier, D., and Meyssignac, B. (2014). Approaches to evaluate the recent impacts of sea-level rise on shoreline changes. *Earth Sci. Rev.* 138, 47–60. doi: 10.1016/j.earscirev.2014.08.005

Le Cozannet, G., Nicholls, R. J., Hinkel, J., Sweet, W. V., McInnes, K. L., Van de Wal, R. S., et al. (2017). Sea level change and coastal climate services: the way forward. *J. Mar. Sci. Eng.* 5:49. doi: 10.3390/jmse5040049

Legeais, J. F., Ablain, M., Zawadzki, L., Zuo, H., Johannessen, J., Schaffenberg, M., et al. (2018). An improved and homogeneous altimeter sea level record from the ESA climate change initiative. *Earth Syst. Sci. Data* 10, 281–301. doi: 10.5194/essd-10-281-2018

Levin, J., Wilkin, J., Fleming, N., and Zavala-Garay, J. (2018). Mean circulation of the Mid-Atlantic Bight from a climatological data assimilative model. *Ocean Model.* 128, 1–14. doi: 10.1016/j.ocemod.2018.05.003

Li, X. H., Yang, G., Chen, J., Zheng, D., and Chen, G. (2018). Using satellite altimetry to calibrate the simulation of typhoon Seth storm surge off Southeast China. *Remote Sens.* 10:657. doi: 10.3390/rs10040657

Lillibridge, J., Lin, M., and Shum, C. K. (2013). Hurricane Sandy storm surge measured by satellite altimetry. *Oceanography* 26, 8–9. doi: 10.5670/oceanog.2013.18

Liu, Y., Kerkering, H., and Weisberg, R. H. (2015). "Introduction to coastal ocean observing systems," in *Coastal Ocean Observing Systems*, eds Y. Liu, H. Kerkering, and R. H. Weisberg (Cambridge, MA: Academic Press), 1–10. doi: 10.1016/b978-0-12-802022-7.00001-8

Loisel, H., Mangin, A., Vantrepotte, V., Dessailly, D., Dinh, D. N., Garnesson, P., et al. (2014). Variability of suspended particulate matter concentration in coastal waters under the Mekong's influence from ocean color (MERIS) remote sensing over the last decade. *Remote Sens. Environ.* 150, 218–230. doi: 10.1016/j.rse.2014.05.006

Luijendijk, A., Hagenaars, G., Ranasinghe, R., Baart, F., Donchyts, G., and Aarninkhof, S. (2018). The state of the world's beaches. *Sci. Rep.* 8:6641.

Madsen, K. S., Høyer, J. L., Fu, W., and Donlon, C. (2015). Blending of satellite and tide gauge sea level observations and its assimilation in a storm surge model of the North Sea and Baltic Sea. *J. Geophys. Res. Oceans* 120, 6405–6418. doi: 10.1002/2015JC011070

Marmet, F. X., Maureau, J., Calaprice, M., and Aguttes, J. P. (2015). GPS/Galileo navigation in GTO/GEO orbit. *Acta Astronaut.* 117, 263–276. doi: 10.1016/j.actaastro.2015.08.008

Martín-Neira, M. (1993). A passive reflectometry and interferometry system (PARIS): application to ocean altimetry. *ESA J.* 17, 331–355.

Martín-Neira, M., D'Addio, S., Buck, C., Floury, N., and Prieto-Cerdeira, R. (2011). The PARIS ocean altimeter in-Orbit demonstrator. *IEEE Trans. Geosci. Remote Sens.* 49(6 Part 2), 2209–2237. doi: 10.1109/TGRS.2010.2092431

Massonnet, D., and Feigl, K. L. (1998). Radar interferometry and its application to changes in the Earth's surface. *Rev. Geophys.* 36, 441–500. doi: 10.1029/97RG03139

Melet, A., Meyssignac, B., Almar, R., and Le Cozannet, G. (2018). Under-estimated wave contribution to coastal sea-level rise. *Nat. Clim. Change* 8, 234–239. doi: 10.1038/s41558-018-0088-y

Menéndez, M., and Woodworth, P. L. (2010). Changes in extreme high water levels based on a quasi-global tide-gauge dataset. *J. Geophys. Res.* 115:C10011. doi: 10.1029/2009JC005997

Milliman, J. D., and Farnsworth, K. L. (2013). *River Discharge to the Coastal Ocean: A Global Synthesis*. Cambridge: Cambridge University Press.

Montojo, F. J., López Moratalla, T., and Abad, C. (2011). Astrometric positioning and orbit determination of geostationary satellites. *Adv. Space Res.* 47, 1043–1053. doi: 10.1016/j.asr.2010.11.025

Nicholls, R. J. (2010). "Impacts of and responses to sea level rise," in *Understanding Sea Level Rise and Variability*, eds J. A. Church, P. L. Woodworth, T. Aarup, and W. S. Wilson (Hoboken, NJ: Wiley-Blackwell).

Nurse, L. A., McLean, R. F., Agard, J., Briguglio, L. P., Duvat-Magnan, V., Pelesikoti, N., et al. (2014). "Small islands," in *Climate Change : Impacts, Adaptation, and Vulnerability; Part B: Regional Aspects; Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds V. R. Barros, C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, et al. (Cambridge: Cambridge University Press), 1613–1654.

Ouillon, S., Douillet, P., and Andréfouët, S. (2004). Coupling satellite data with in situ measurements and numerical modeling to study fine suspended-sediment transport: a study for the lagoon of New Caledonia. *Coral Reefs* 23, 109–122. doi: 10.1007/s00338-003-0352-z

Parrinello, T., Shepherd, A., Bouffard, J., Badessi, S., Casal, T., Davidson, M., et al. (2018). CryoSat: ESA's ice mission – Eight years in space. *Adv. Space Res.* 62, 1178–1190. doi: 10.1016/j.asr.2018.04.014

Pascual, A., Bouffard, J., Ruiz, S., Nardelli, B. B., Vidal-Vijande, E., Escudier, R., et al. (2013). Recent improvements in mesoscale characterization of the western Mediterranean Sea: synergy between satellite altimetry and other observational approaches. *Sci. Mar.* 77, 19–36. doi: 10.3989/scimar.03740.15A

Pascual, A., Lana, A., Troupin, C., Ruiz, S., Faugère, Y., Escudier, R., et al. (2015). Assessing SARAL/AltiKa data in the coastal zone: comparisons with HF radar observations. *Mar. Geod.* 38, 260–276. doi: 10.1080/01490419.2015.1019656

Pascual, A., Ruiz, S., Olita, A., Troupin, C., Claret, M., Casas, B., et al. (2017). A multiplatform experiment to unravel meso- and submesoscale processes in an intense front (AlborEx). *Front. Mar. Sci.* 4:39. doi: 10.3389/fmars.2017.00039

Passaro, M., Cipollini, P., and Benveniste, J. (2015a). Annual sea level variability of the coastal ocean: the Baltic Sea-North Sea transition zone. *J. Geophys. Res. Oceans* 120, 3061–3078. doi: 10.1002/2014JC010510

Passaro, M., Fenoglio-Marc, L., and Cipollini, P. (2015b). Validation of significant wave height from improved satellite altimetry in the German Bight. *IEEE Trans. Geosci. Remote Sens.* 53, 2146–2156. doi: 10.1109/TGRS.2014.2356331

Passaro, M., Cipollini, P., Vignudelli, S., Quartly, G. D., and Snaith, H. M. (2014). ALES: a multi-mission adaptive subwaveform retracker for coastal and open ocean altimetry. *Remote Sens. Environ.* 145, 173–189. doi: 10.1016/j.rse.2014.02.008

Passaro, M., Dinardo, S., Quartly, G. D., Snaith, H. M., Benveniste, J., Cipollini, P., et al. (2016). Cross-calibrating ALES Envisat and CryoSat-2 Delay–Doppler: a coastal altimetry study in the Indonesian Seas. *Adv. Space Res.* 58, 289–303. doi: 10.1016/j.asr.2016.04.011

Passaro, M., Rose, S. K., Andersen, O. B., Boergens, E., Calafat, F. M., Dettmering, D., et al. (2018). ALES+: adapting a homogenous ocean retracker for satellite altimetry to sea ice leads, coastal and inland waters. *Remote Sens. Environ.* 211, 456–471. doi: 10.1016/j.rse.2018.02.074

Peltier, W. R. (2004). Global glacial isostasy and the surface of the ice-age Earth. *Annu. Rev. Earth Planet. Sci.* 32, 111–149. doi: 10.1146/annurev.earth.32.082503.144359

Peng, F., and Deng, X. (2018). A new retracking technique for Brown peaky altimetric waveforms. *Mar. Geod.* 41, 99–125. doi: 10.1080/01490419.2017.1381656

Piccioni, G., Dettmering, D., Passaro, M., Schwatke, C., Bosch, W., and Seitz, F. (2018). Coastal improvements for tide models: the impact of ALES retracker. *Remote Sens.* 10:700. doi: 10.3390/rs10050700

Piecuch, C. G., Bittermann, K., Kemp, A. C., Ponte, R. M., Little, C. M., Engelhart, S. E., et al. (2018). River-discharge effects on United States Atlantic and Gulf coast sea-level changes. *Proc. Natl. Acad. Sci. U.S.A.* 115, 7729–7734. doi: 10.1073/pnas.1805428115

Poupardin, A., Poupardin, A., Idier, D., Michele, M., and Raucoules, D. (2016). Water depth inversion from a single SPOT-5 dataset. *IEEE Trans. Geosci. Remote Sens.* 54, 2329–2342. doi: 10.1109/TGRS.2015.2499379

Pugh, D. T., and Woodworth, P. L. (2014). *Sea-Level Science: Understanding Tides, Surges, Tsunamis and Mean Sea-Level Changes*. Cambridge: Cambridge University Press.

Ranasinghe, R. (2016). Assessing climate change impacts on open sandy coasts: a review. *Earth Sci. Rev.* 160, 320–332. doi: 10.1016/j.earscirev.2016.07.011

Raney, K. R. (1998). The Delay Doppler radar altimeter. *IEEE Trans. Geosci. Remote Sens.* 36, 1578–1588. doi: 10.1109/36.718861

Raucoules, D., Cozanneta, G., Wöppelmann, G., Michele, M., Gravelle, M., Daag, A., et al. (2013). High nonlinear urban ground motion in Manila (Philippines) from 1993 to 2010 observed by DInSAR: implications for sea-level measurement. *Remote Sens. Environ.* 139, 386–397. doi: 10.1016/j.rse.2013.08.021

Ray, C., Martin-Puig, C., Clarizia, M. P., Ruffini, G., Dinardo, S., Gommenginger, C., et al. (2015). SAR altimeter backscattered waveform model. *IEEE Trans. Geosci. Remote Sens.* 53, 911–919. doi: 10.1109/TGRS.2014.2330423

Ray, R. D., and Egbert, G. D. (2017). "Tides and satellite altimetry," in *Satellite Altimetry over Oceans and Land Surfaces*, eds D. Stammer and A. Cazenave (Boca Raton, FL: CRC Press), 427–458. doi: 10.1201/9781315151779-13

Restano, M., Passaro, M., and Benveniste, J. (2018). New achievements in coastal altimetry. *Eos* 99. doi: 10.1029/2018EO106087

Ribó, S., Arco, J. C., Oliveras, S., Cardellach, E., Rius, A., and Buck, C. (2014). Experimental results of an X-Band PARIS receiver using digital satellite TV opportunity signals scattered on the sea surface. *IEEE Trans. Geosci. Remote Sens.* 52, 5704–5711. doi: 10.1109/TGRS.2013.2292007

Rodriguez, E., Fernandez, D. E., Peral, E., Curtis, C., De Bleser, J. W., and Williams, B. (2018). "Wide-swath altimetry a review, in satellite altimetry over oceans and land surfaces," in *Satellite Altimetry Over Oceans and Land Surfaces Earth Observation of Global Changes Book Series*, eds D. Stammer and A. Cazenave (London: CRC Press), 644.

Roscher, R., Uebbing, B., and Kusche, J. (2017). STAR: spatio-temporal altimeter waveform retracking using sparse representation and conditional random fields. *Remote Sens. Environ.* 201, 148–164. doi: 10.1016/j.rse.2017.07.024

Rosengren, M., De Vicente-Olmedo, J., and Pedersen, F. (2004). Keeping track of geostationary satellites - a novel and less costly approach. *ESA Bull.* 119, 64–68.

Rubio, A., Caballero, A., Orfila, A., Hernández-Carrasco, I., Ferrer, L., González, M., et al. (2018). Eddy-induced cross-shelf export of high Chl-a coastal waters in the SE Bay of Biscay. *Remote Sens. Environ.* 205, 290–304. doi: 10.1016/j.rse.2017.10.037

Ruiz, S., Pascual, A., Garau, B., Faugère, Y., Alvarez, A., and Tintoré, J. (2009). Mesoscale dynamics of the Balearic Front, integrating glider, ship and satellite data. *J. Mar. Syst.* 78, S3–S16. doi: 10.1016/j.jmarsys.2009.01.007

Salazar-Ceciliano, J., Trasviña-Castro, A., and González-Rodríguez, E. (2018). Coastal currents in the Eastern Gulf of Tehuantepec from coastal altimetry. *Adv. Space Res.* 62, 866–873. doi: 10.1016/j.asr.2018.05.033

Shah, R., and Garrison, J. L. (2017). Precision of Ku-band reflected signals of opportunity altimetry. *IEEE Geosci. Remote Sens. Lett.* 14, 1840–1844. doi: 10.1109/LGRS.2017.2737949

Shah, R., Garrison, J. L., and Grant, M. S. (2012). Demonstration of bistatic radar for ocean remote sensing using communication satellite signals. *IEEE Geosci. Remote Sens. Lett.* 9, 619–623. doi: 10.1109/LGRS.2011.2177061

Smith, W. H., Leuliette, E. W., Passaro, M., Quartly, G., and Cipollini, P. (2017). "Covariant errors in ocean retrackers evaluated using along-track cross-spectra," in *Proceedings of the Ocean Surface Topography Science Team (OSTST) Meeting*, Miami, FL.

Smith, W. H., and Scharroo, R. (2015). Waveform aliasing in satellite radar altimetry. *IEEE Trans. Geosci. Remote Sens.* 53, 1671–1682. doi: 10.1109/TGRS.2014.2331193

Stanev, E., Schulz-Stellenfleth, J., Staneva, J., Grayek, S., Grashorn, S., Behrens, A., et al. (2016). Ocean forecasting for the German Bight: from regional to coastal scales. *Ocean Sci.* 12, 1105–1136. doi: 10.5194/os-12-1105-2016

Staneva, J., Alari, V., Breivik, Ø., Bidlot, J.-R., and Mogensen, K., (2017). Effects of wave-induced forcing on a circulation model of the North Sea. *Ocean Dyn.* 67, 81–101. doi: 10.1007/s10236-016-1009-0

Staneva, J., Wahle, K., Koch, W., Behrens, A., Fenoglio-Marc, L., and Stanev, E. (2016). Coastal flooding: impact of waves on storm surge during extremes. A case study for the German Bight. *Nat. Hazards Earth Syst. Sci.* 16, 2373–2389. doi: 10.5194/nhess-2016-227

Suanez, S., Manuel, G., Thomas, B., Mathias, R., Loïc, L., Laurence, D., et al. (2012). Les observatoires du trait de côte en France métropolitaine et dans les DOM. *EchoGéo* 19. doi: 10.4000/echogeo.12942

Syvitski, J. P., Vörösmarty, C. J., Kettner, A. J., and Green, P. (2005). Impact of humans on the flux of terrestrial sediment to the global coastal ocean. *Science* 308, 376–380. doi: 10.1126/science.1109454

Tamisiea, M. E. (2011). Ongoing glacial isostatic contributions to observations of sea level change. *Geophys. J. Int.* 186, 1036–1044. doi: 10.1111/j.1365-246X.2011.05116.x

Taramelli, A., Matteo, L. D., Ciavola, P., Guadagnano, F., and Tolomeid, C. (2015a). Temporal evolution of patterns and processes of the coastal area in Bevano Estuary (Northern Adriatic) Italy. *Ocean Coast. Manag.* 108, 74–88. doi: 10.1016/j.ocecoaman.2014.06.021

Taramelli, A., Valentini, E., and Cornacchia, L. (2015b). "Remote sensing solutions to monitor biotic and abiotic dynamics in coastal ecosystems," in *Coastal Zones Solutions for the 21st Century*, Vol. 8, eds J. Baztan, O. Chouinard, B. Jorgensen, P. Tett, J.-P. Vanderlinden, and L. Vasseur (Amsterdam: Elsevier), 125–135.

Taramelli, A., Valentini, E., Cornacchia, L., Monbaliu, J., Thompson, R. C., Mandrone, S., et al. (2014). Modeling uncertainty in estuarine system by means of combined approach of optical and radar remote sensing. *Coast. Eng.* 87, 77–96. doi: 10.1016/j.coastaleng.2013.11.001

Tarpanelli, A., Brocca, L., Barbetta, S., Faruolo, M., Lacava, T., and Moramarco, T. (2015). Coupling MODIS and radar altimetry data for discharge estimation in poorly gauged river basins. *IEEE J. Sel. Top. Appl.* 8, 141–148. doi: 10.1109/jstars.2014.2320582

The WCRP Global Sea Level Budget Group (2018). Global sea level budget, 1993-present. *Earth Syst. Sci. Data* 10, 1551–1590. doi: 10.5194/essd-10-1551-2018

Toublanc, F., Ayoub, N. K., Lyard, F., Marsaleix, P., and Allain, D. J. (2018). Tidal downscaling from the open ocean to the coast: a new approach applied to the Bay of Biscay. *Ocean Model.* 124, 16–32. doi: 10.1016/j.ocemod.2018.02.001

Troupin, C., Pascual, A., Valladeau, G., Pujol, I., Lana, A., Heslop, E., et al. (2015). Illustration of the emerging capabilities of SARAL/AltiKa in the coastal zone using a multi-platform approach. *Adv. Space Res.* 55, 51–59. doi: 10.1016/j.asr.2014.09.011

Turki, I., Laignel, B., Chevalier, L., Costa, S., and Massei, N. (2015). On the investigation of the sea level variability in coastal zones using SWOT satellitemission: example of the eastern English Channel (western France). *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* 8, 1564–1569. doi: 10.1109/JSTARS.2015.2419693

Verron, J., Bonnefond, P., Aouf, L., Birol, F., Bhowmick, S. A., and Calmant, S. (2018). The benefits of the Ka-Band as evidenced from the SARAL/AltiKa altimetric mission: scientific applications. *Remote Sens.* 10:163. doi: 10.3390/rs10020163

Verron, J., Sengenes, P., Lambin, J., Noubel, J., Steunou, N., Guillot, A., et al. (2015). The SARAL/AltiKa altimetry satellite mission. *Mar. Geod.* 38, 2–21. doi: 10.1080/01490419.2014.1000471

Vignudelli, S., Cipollini, P., Roblou, L., Lyard, F., Gasparini, G. P., Manzella, G., et al. (2005). Improved satellite altimetry in coastal systems: case study of the Corsica Channel (Mediterranean Sea). *Geophys. Res. Lett.* 32:L07608. doi: 10.1029/2005GL022602

Vignudelli, S., Kostianoy, A. G., Cipollini, P., and Benveniste, J. (eds). (2011). *Coastal Altimetry*. Berlin: Springer-Verlag, 578. doi: 10.1007/978-3-642-12796-0

Vitousek, S., Barnard, P. L., Fletcher, C. H., Frazer, N., Erikson, L., Curt, D., et al. (2017). Doubling of coastal flooding frequency within decades due to sea-level rise. *Sci. Rep.* 7:1399. doi: 10.1038/s41598-017-01362-7

Vousdoukas, M. I., Mentaschi, L., Voukouvalas, E., Verlaan, M., Jevrejeva, S., and Jackson, L. P. (2018). Global probabilistic projections of extreme sea levels show intensification of coastal flood hazard. *Nat. Commun.* 9:2360. doi: 10.1038/s41467-018-04692-w

Vu, P. L., Frappart, F., Darrozes, J., Marieu, V., Blarel, F., Ramillien, G., et al. (2018). Multi-satellite altimeter validation along the French Atlantic coast in the southern bay of Biscay from ERS-2 to SARAL. *Remote Sens.* 10:93. doi: 10.3390/rs10010093

Wahle, K., Staneva, J., Koch, W., Fenoglio, L., Ho-Hagemann Ha, T., and Stanev, E. (2017). An atmosphere-wave regional coupled model: improving predictions of wave heights and surface winds in the southern North Sea. *Ocean Sci.* 13, 289–301. doi: 10.5194/os-13-289-2017

Warrick, J. A., Mertes, L. A. K., Siegel, D. A., and Mackenzie, C. (2004). Estimating suspended sediment concentrations in turbid coastal waters of the Santa Barbara Channel with SeaWiFS. *Int. J. Remote Sens.* 25, 1995–2002. doi: 10.1080/01431160310001619535

Wickert, J., Cardellach, E., Martin-Neira, M., Bandeiras, J., Bertino, L., Andersen, O. B., et al. (2016). GEROS-ISS: GNSS REflectometry, radio occultation, and scatterometry onboard the international space station. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* 9, 4552–4581. doi: 10.1109/JSTARS.2016.2614428

Wiese, A., Staneva, J., Schultz-Stellenfleth, J., Behrens, A., Fenoglio-Marc, L., and Bidlot, J. R. (2018). Synergy between satellite observations and model simulations during extreme events. *Ocean Sci.* 14, 1503–1521. doi: 10.5194/os-14-1503-2018

Woodworth, P. L., Hunter, J. R., Marcos, M., Caldwell, P., Menéndez, M., and Haigh, I. (2016). Towards a global higher-frequency sea level data set. *Geosci. Data J.* 3, 50–59. doi: 10.1002/gdj3.42

Woodworth, P. L., Melet, A., Marcos, M., Ray, R. D., Wöppelmann, G., Sasaki, Y. N., et al. (2019). Forcing factors affecting sea level changes at the coast. *Surv. Geophys.* doi: 10.1007/s10712-019-09531-1

Woodworth, P. L., Melissa, M., and Roland, G. W. (2011). Evidence for century-timescale acceleration in mean sea levels and for recent changes in extreme sea levels. *Surv. Geophys.* 32, 603–618. doi: 10.1007/978-94-007-2063-3_18

Woodworth, P. L., Wöppelmann, G., Marcos, M., Gravelle, M., and Bingley, R. M. (2017). Why we must tie satellite positioning to tide gauge data. *Eos* 98, 13–15. doi: 10.1029/2017EO064037

Wöppelmann, G., Cozannet, G. L., Michele, M., Raucoules, D., Cazenave, A., Garcin, M., et al. (2013). Is land subsidence increasing the exposure to sea level rise in Alexandria, Egypt? *Geophys. Res. Lett.* 40, 2953–2957. doi: 10.1002/grl.50568

Wöppelmann, G., and Marcos, M. (2016). Vertical land motion as a key to understanding sea level change and variability. *Rev. Geophys.* 54, 64–92. doi: 10.1002/2015RG000502

Wöppelmann, G., Martin-Miguez, B., Bouin, M. N., and Altamimi, Z. (2007). Geocentric sea-level trend estimates from GPS analyses at relevant tide gauges world-wide. *Glob. Planet. Change* 57, 396–406. doi: 10.1016/j.gloplacha.2007.02.002

Xu, X. Y., Birol, F., and Cazenave, A. (2018). Evaluation of coastal sea level offshore Hong Kong from Jason-2 altimetry. *Remote Sens.* 10:282. doi: 10.3390/rs10020282

Yang, L., Lin, M., Liu, Q., and Pan, D. (2012). A coastal altimetry retracking strategy based on waveform classification and sub-waveform extraction. *Int. J. Remote Sens.* 33, 7806–7819. doi: 10.1080/01431161.2012.701350

Young, I. R., Zieger, S., and Babanin, A. V. (2011). Global trends in wind speed and wave height. *Science* 332, 701–702. doi: 10.1038/ngeo2262

Zavorotny, V. U., and Voronovich, A. G. (2000). Scattering of GPS signals from the ocean with wind remote sensing application. *IEEE Trans. Geosci. Remote Sens.* 38, 951–964. doi: 10.1109/36.841977

Zheng, C. W., Pan, J., and Yin, L. C. (2016). Global oceanic wind speed trends. *Ocean Coast. Manag.* 129, 15–24. doi: 10.1016/j.ocecoaman.2016.05.001

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A Response to Scientific and Societal Needs for Marine Biological Observations

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Development of global ocean observing capacity for the biological EOVs is on the cusp of a step-change. Current capacity to automate data collection and processing and to integrate the resulting data streams with complementary data, openly available as FAIR data, is certain to dramatically increase the amount and quality of information and knowledge available to scientists and decision makers into the future. There is little doubt that scientists will continue to expand their understanding of what lives in the ocean, where it lives and how it is changing. However, whether this expanding information stream will inform policy and management or be incorporated into indicators for national reporting is more uncertain. Coordinated data collection including open sharing of data will help produce the consistent evidence-based messages that are valued by managers. The GOOS Biology and Ecosystems Panel is working with other global initiatives to assist this coordination by defining and implementing Essential Ocean Variables. The biological EOVs have been defined, are being updated following community feedback, and their implementation is underway. In 2019, the coverage and precision of a global ocean observing system capable of addressing key questions for the next decade will be quantified, and its potential to support the goals of the UN Decade of Ocean Science for Sustainable Development identified. Developing a global ocean observing system for biology and ecosystems requires parallel efforts in improving evidence-based monitoring of progress against international agreements and the open data, reporting and governance structures that would facilitate the uptake of improved information by decision makers.

Keywords: GOOS, capacity development, EOV, ocean observing, essential ocean variable, UN Decade, Sustainable Development Goals

INTRODUCTION

The Earth, including its atmosphere, land, and ocean ecosystems is changing more rapidly than human societies have experienced in the past two millennia (Poloczanska et al., 2013; Rhein et al., 2013; Schmidtko et al., 2017; Stock et al., 2017). Changes in the ocean are occurring at many levels. There is substantial evidence of overfishing, affecting both target and non-target species (e.g., Watson et al., 2017), leading to population, community and ecosystem level impacts in coastal (Jennings and Kaiser, 1998), deep sea (Koslow et al., 2000) and pelagic environments (Crespo and Dunn, 2017). Shallow tropical coral species are experiencing widespread bleaching, predation such as by the crown of thorns starfish in the Pacific, or replacement by fast-growing algae because of nutrients and other pollutants introduced by humans in many localities (Hughes et al., 2017), affecting local community food security and tourism. Deep-sea coral communities are being affected by fishing and climate change (Williams et al., 2010; Thresher et al., 2011).

Current science and monitoring activities have provided clear evidence of changes at the scale of our planet attributable to intense human activities and complex and long-term changes in environmental parameters. These changes are impacting the distribution and phenology of marine biota (Poloczanska et al., 2013). Sustained monitoring of animal and plant populations and habitats is needed to characterize where and how fast these changes are occurring, where populations and communities are resilient to such change, and where losses of some species and the appearance of new species are impacting human health and the economy, both positively and negatively. This information will assist: (1) local communities to prepare and respond to coming changes; (2) national governments to manage adaptively across the domains of ecology, socioeconomics and governance; and (3) global institutions to develop appropriate policies and globally coordinated support. This will assist maritime nations to respond to our changing environment, while being confident that other nations are undertaking similar actions in word and deed. Sustained monitoring is needed to identify what works, what does not, and where future evidence-based investments are most likely to effect long-term positive change.

Many international treaties have highlighted the speed of current change in biological communities and the negative impacts that lack of action will have on sustainable development. Specifying and developing a sustained observing system that can improve knowledge for action at the many spatial scales of governance and ecosystem structure is no trivial task. It requires identifying the key questions, assessing existing observing system coverage and intensity, prioritization of future investments, capacity development and technology transfer. System coverage needs to be extended to the most critical areas for each issue, with regular reviews of system performance. Critically, the global system will need to attract substantial resourcing, often at the national level, if it is to provide the sustained observations that are needed to drive policy and support managed change.

Developing a global observing system for the biological ocean is fortunately becoming a technical reality. Sustained biological observation of the oceans began only 100 years ago, became regional in the 1930s and underwent a notable rise in the mid-70s that has continued to the present day (Miloslavich et al., 2018a). Rapid technology development in automation and miniaturization are increasing the scale and scope of scientific endeavors thus making observing programs increasingly data-rich, cost-effective and ultimately more likely to be sustained.

Some new technologies expand traditional data streams, while others open new ones. Thirty years of remote sensing support detailed analysis of trends in ocean color and surface productivity (e.g., Dunstan et al., 2018), while advances in artificial intelligence and machine learning provide increasingly rapid and consistent classification and processing of underwater imagery and marine fauna (Goetze et al., 2019). Advances in ‘omics support new monitoring approaches such as Close-Kin Mark Recapture which can census adult populations without ever sampling an adult (Hillary et al., 2018), and environmental DNA which can identify species and populations from the water they swim in (Sigsgaard et al., 2016). Miniature genomic processors (e.g., nanopore sequencing, Brown et al., 2017) will soon be able to sequence DNA remotely on Autonomous vehicles including profiling floats and gliders, leading to a massive increase in information. Not all approaches will be suitable for monitoring but even they will improve our knowledge of system structure and function that will direct and assist interpretation of monitoring programs.

Developing a global biological monitoring system for the ocean also requires a cultural change in the way that marine scientists (especially biologists) share their data. We have an opportunity with the UN Decade of Ocean Science for Sustainable Development (UN Decade) to realize the expectation that making scientific data open and accessible under FAIR principles is the default for data platforms and researchers (Stall et al., 2019). A lasting legacy of the UN Decade would be if marine biologists were to share their data as openly as physical oceanographers do already.

In 2015, the Global Ocean Observing System of the Intergovernmental Oceanographic Commission of UNESCO (GOOS) identified the need to expand their role in ocean observing to the biological realm and added the Biology and Ecosystems Panel (BioEco) to the existing Physics and

Biogeochemistry panels. GOOS has been among the groups leading the development of global sustained observations for physics and biogeochemistry, supporting the needs of science and policy through the IPCC among others.

In section "Introduction" of this paper, we review the process to date in identifying the biological Essential Ocean Variables (EOVs), and how the international community has been engaged in their validation, integration and implementation. Section "Building the Leadership and Community Support" identifies many of the (substantial) tasks remaining before a global ocean observing system for biology and ecosystems can become operational. A brief description of the need for each EOV, supporting EOVs, and the challenges and recommendations for their future development, including links to other important initiatives is provided in section "Status of Implementing the Biological EOVs.". Section "Organizational Structure and Challenges" identifies the complex scientific and reporting environment that continued EOV development will need to operate in and gain support from. Future developments and directions are briefly discussed in section "Future Directions and Developments."

BUILDING THE LEADERSHIP AND COMMUNITY SUPPORT

The role of the GOOS panels is to identify and set the requirements for EOVs, followed by the development of a coordinated implementation strategy. Implementation is based on collection standards and the interoperability of data and information products. Once the Biology and Ecosystem Panel was established in 2015, it outlined an initial set of activities, targets and products (**Figure 1**).

The first task was to *identify* a set of biological EOVs guided by the Framework for Ocean Observing (Lindstrom et al., 2012). EOVs are selected to have high impact and high feasibility. EOV impact is defined as their relevance to solving science questions, addressing societal needs and their contribution to improved marine resource management. Feasibility required EOVs to be scientifically credible, technically practical and cost effective. To identify the biological EOVs, the panel adopted a process that (1) linked to international initiatives and issues, (2) was transparent, (3) was inclusive, and (4) was peer reviewed. Twenty-four international conventions and/or multilateral agreements relevant to marine life were surveyed in support of EOV selection. The current state of ocean observation networks and the uptake of EOVs in addressing societal and scientific issues were used to identify feasibility (**Figure 2**; Miloslavich et al., 2018a).

Biological EOVs (**Table 1**) focus on the status and change of ecosystem components (microbial communities, phytoplankton, zooplankton, fish, marine turtles, birds, mammals), and habitats (hard coral, seagrass, mangrove and macroalgae), with additional EOVs being developed as time and circumstances require (current emerging EOVs are for benthic invertebrate and microbes; Miloslavich et al., 2018a). A separate GOOS project is developing a Deep Ocean Observing Strategy (DOOS; Levin et al., 2019). This project will work with the three panels to identify

FIGURE 1 | Schematic of the tasks identified by the GOOS Biology and Ecosystems Panel to develop a sustained observing system.

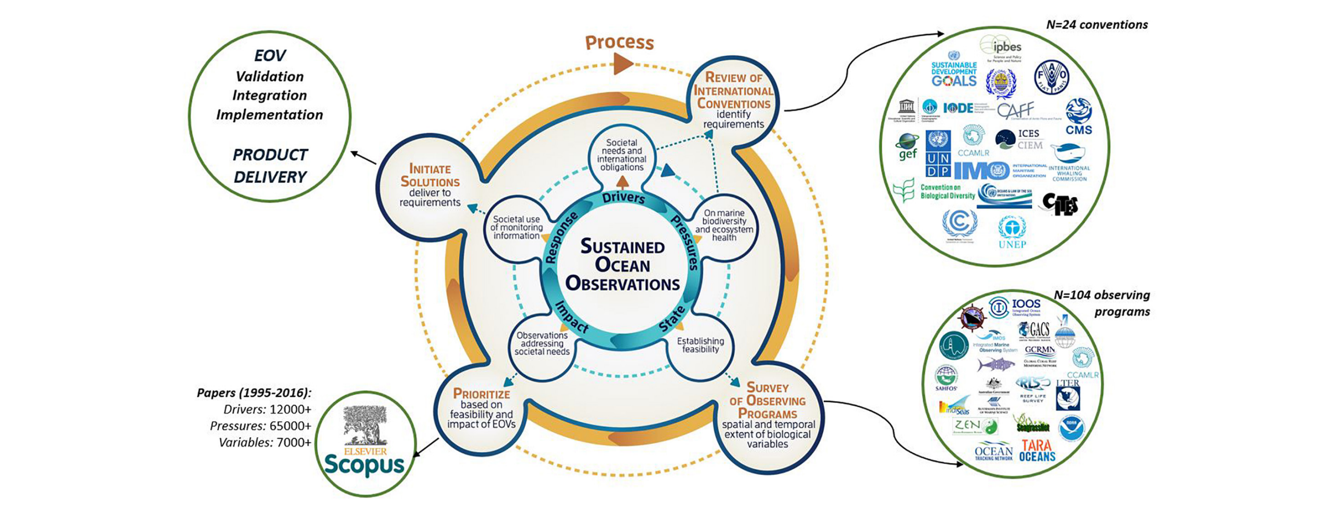

FIGURE 2 | Process used to identify the biological EOVs following the commonly applied Driver Pressure State Impact Response (DPSIR) model (updated from Miloslavich et al., 2018a).

TABLE 1 | Essential Ocean Variables identified for each GOOS panel.

Physics	Biogeochemistry	Biology and ecosystems
• Sea state	• Oxygen	• Phytoplankton biomass and diversity
• Ocean surface stress	• Inorganic carbon	• Zooplankton biomass and diversity
• Ocean surface heat flux	• Transient tracers	• Fish abundance and distribution
• Sea ice	• Particulate matter	• Marine turtles, birds and mammals abundance and distribution
• Sea surface height	• Nutrients	• Hard coral cover and composition
• Sea surface temp	• Nitrous oxide	• Seagrass cover and composition
• Subsurface temperature	• Dissolved organic carbon	• Mangrove cover and composition
• Surface currents	• Ocean color	• Macroalgal cover and composition
• Subsurface currents	• Stable carbon isotopes	• Microbe biomass and diversity (emerging)
• Sea surface salinity		• Invertebrate abundance and distribution (emerging)
• Subsurface salinity		• Ocean Sound

Subvariables provide further specification and are listed in the specification sheets (www.goosocean.org). DOOS is working with the panels to identify where modifications or additional EOVs are needed specifically for monitoring the deep ocean.

where existing EOVs need to be extended or new ones added. Cross-disciplinary EOVs including ocean color, and ocean sound are directly relevant to understand the physical, biogeochemical, and biological properties of the ocean but are housed in one of the three panels. There is an ongoing discussion of how human pressure EOVs (e.g., marine debris) could be developed, perhaps through linking to existing groups active in these areas.

The second task was to *validate* these biological EOVs with stakeholders to maximize the probability of their uptake and use by the scientific, climate and policy communities – which could be quite different for each EOV. Scientific communication through refereed papers (Bax et al., 2018; Miloslavich et al., 2018a,b; Muller-Karger et al., 2018b), presentations at key conferences (e.g., the American Geophysical Union – Ocean Sciences Conference, the World Conference of Marine Biodiversity, the Effects of Climate Change on the World's Oceans International Symposium, the bi-annual conference of International Society for Microbial Ecology and many more specialized meetings), and the drafting of peer-reviewed technical specification sheets for each of the EOVs[1] were part of the validation process. Several biological EOVs were taken up as Essential Climate Variables (ECVs), part of the Global Climate Observing System (GCOS) (World Meteorological Organization [WMO], 2016). Engagement with the policy makers was through joint workshops including groups with reporting and assessment responsibilities as well as country representatives likely to use the information for their own management and reporting (UNEP/CBD/SBSTTA/20/16/Page 121).

The third task was to *integrate* these biological EOVs within current observing efforts. Standard operating procedures and best practices for collecting, analysing and sharing information will increase scientific impact at regional and global levels and help justify building investment in a sustained observing system. An agreement was signed with the Marine Biodiversity Observation Network (MBON), a theme of the Group on Earth Observations Biodiversity Observation Network (GEO BON)

[1] http://www.goosocean.org/eov

and the Ocean Biogeographic Information System (OBIS). This agreement supports the development of a globally coordinated and sustained observing system sharing open access data and best practices, and facilitating capacity development[2]. This group of three subsequently partnered with the GEO Blue Planet initiative.

Integration of biological EOVs with established observing networks, including some of the GOOS Regional Alliances (e.g., the US Integrated Ocean Observing System – IOOS, the Australian Integrated Marine Observing System – IMOS, and the Southern Ocean Observing System – SOOS), has started (**Figure 3**). Collaboration with other groups including Future Earth, the Research Coordination Network under the U.S. National Science Foundation, and working groups of the Scientific Committee for Oceanic Research (SCOR) (e.g., plankton, Boss et al., 2018) is developing. Integration of the three GOOS disciplines (physics, biogeochemistry and biology) is occurring through major ocean phenomena that require cross-disciplinary observation.

Implementation, the fourth task, is occurring through workshops for each EOV. GOOS panels do not have the capacity or technical resources to develop new observing networks, but through coordinating existing networks and platforms, aim to improve the comparability and openness of existing data collections. The workshops bring together teams of international experts to discuss how to develop a global, coordinated strategy for monitoring each EOV, identify the relevant existing datasets and networks, review technological monitoring approaches and best practices, and identify gaps in geographic or system coverage that need to be addressed. Once the scope of the global network for an EOV is identified, the GOOS panels will work with existing networks and platforms to expand their scope of activities through technology transfer and targeted capacity development.

[2]http://www.iobis.org/documents/GOOS-BioEco-OBIS-GEOBON-MBON_collaboration_SIGNED.pdf

Best practices are an important first step in being able to share data and relevant metadata in a meaningful fashion. Developing best practices requires international agreement, coordination, funding, publication and active promotion. GOOS, MBON, and others work with the Intergovernmental Oceanographic Commission (IOC) Ocean Best Practices Working Group to develop workflows to document, implement and continually update Best Practices for EOVs and identified subvariables. An essential component of best practices is promoting open data shared promptly. The lack of open data is one of the most significant impediments to developing a global observing system for ocean biology and ecosystems. Data sharing policies are particularly important for data that might be of commercial, cultural or other importance.

As of November 2018, three implementation workshops had taken place for coral, plankton and macroalgal EOVs. Workshops have been organized opportunistically in collaboration with other groups. The role of GOOS has been mostly to facilitate, coordinate and support integration within the different networks so that the EOVs are organized following a common framework and progressed to a more mature stage. For example, the coral EOV builds on long time efforts by the Global Coral Reef Monitoring Network (GCRMN), the zooplankton EOV builds on the Global Alliance of Continuous Plankton Recorders (GACs) and includes future automated technologies on global platforms, while the macroalgal EOV builds on a long history of individual coastal monitoring programs updated to include newer automated technologies.

REMAINING TASKS

The Panel has rapidly progressed through their tasks identified in the Framework for Ocean Observing (Lindstrom et al., 2012), since 2016, but much remains to be done, particularly for

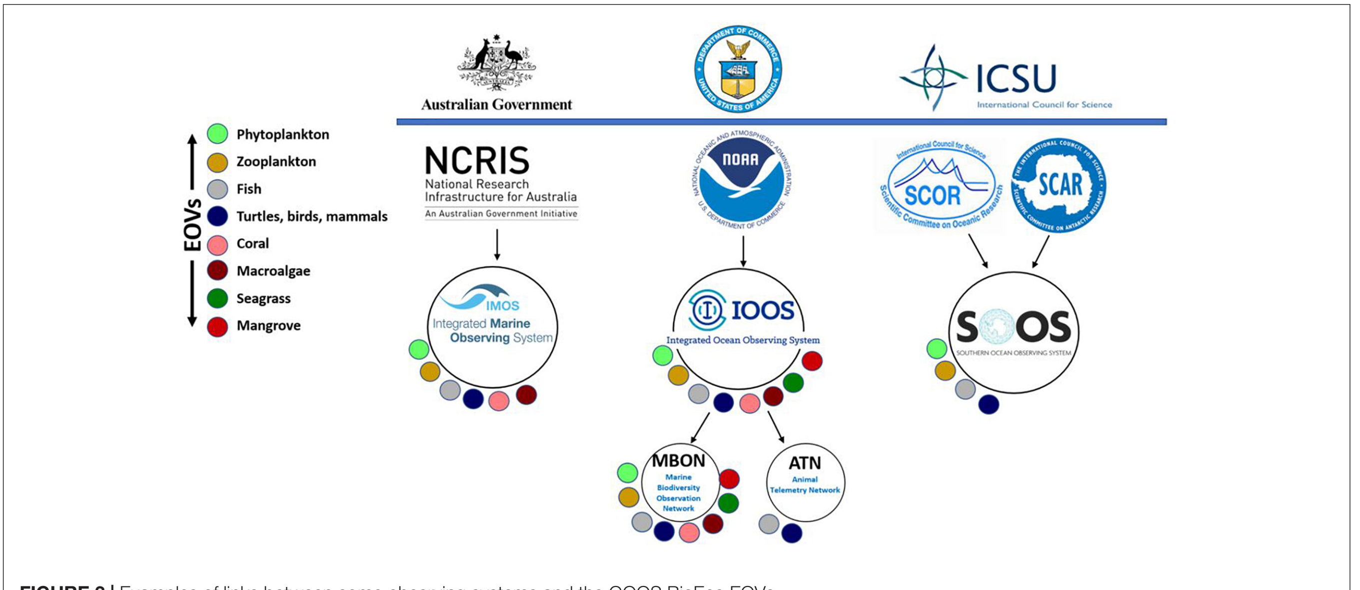

FIGURE 3 | Examples of links between some observing systems and the GOOS BioEco EOVs.

validation, integration and implementation. EOV identification will be progressively refined, guided by new priorities or scientific advances (as is happening with the microbial EOV) and based on community feedback (as is happening for the deep ocean, Levin et al., 2019).

Validation

A critical next step is completing the identification of existing observing networks and elements and comparing this to the desired geographical and temporal coverage. The Panel will be working on this with additional experts supported by a PEGASuS (Future Earth/NCEAS) grant to identify priority gaps to target through the UN Decade. This will require a parallel task in data and information management to ensure that collected data are available for regional and global management and reporting.

Integration

A global ocean observing system is not something that one group is likely to achieve by itself. Ongoing coordination will be required to agree on best practices, improve efficiencies, fill gaps, and reduce any redundancies. Standard operating procedures and best practices do not have to be prescriptive, but do require attention to design, deployment and recording so that comparison of measurements made in different places or in time series to detect and accurately quantify change can be made and confidently communicated to decision makers and policy makers (Przeslawski et al., 2019).

Integration of the scientific, management, and policy environments is also needed to establish a global observing system that is relevant and supported. This will require improving how scientific information is used to support management and policy decisions at all levels of government. For example, indicators chosen for reporting against international conventions and agreements, such as SDG 14 or CBD biodiversity targets, are frequently based on lowest common denominator options so that all countries can participate. The marine science community needs to work within the policy environment to help develop more informative, quantitative indicators that provide direct information on trends in the state of the marine environment. Nested or hierarchical indicators so that countries can track their progress at the level in the hierarchy appropriate to their level of development is one approach to achieve greater relevance (Dunstan et al., 2016). Increasing the relevance of monitoring data to the management and policy environments will help incentivise and target capacity development and technology transfer.

Implementation

The UN Decade provides a useful time-frame and target to build the comprehensive and sustainable global ocean observing system for biology. This time-frame matches that for Agenda 2030, and the observing system will be able to support countries reporting against the Sustainable Development Goals. Improved consistency and improved access to data under FAIR principles will provide the means to answer scientific questions that no one institute could achieve. The UN Decade has an opportunity to shift the culture of science and data collection of marine biological data to one that is more open, more collaborative and has greater impact.

Improved capacity development and technology transfer will be required, especially if monitoring is to be sustained – a common failing of many existing initiatives, especially in Least Developed Countries and Small Island Developing States. Linking capacity development and technology transfer to sustained monitoring may provide an opportunity provide enduring networks and connections between scientists in the developing and developed world that will keep scientists engaged over the long term (Bax et al., 2018). Improved ocean observing capacity will underpin the growth of the Blue Economy and is critical to sustainable development.

Iteration

A sustained global ocean observing system will require constant adjustment and tuning especially during its development stage, but also as new questions and ways of collecting information gain priority. Physical oceanographers have the advantage of globally integrating models, whereas many populations, species, and habitats are localized and require individual attention. Maintaining a backbone of sustained, consistent, and inter-operable observations to monitor long-term change at the regional and global scale, while making the most of opportunities from more local studies will be one of the continuing challenges for sustained biological observation. It will be equally important to support, the aggregation of information from local to regional, and from regional to global reporting to improve the relevance and uptake of monitoring information (e.g., Harrison et al., 2018).

STATUS OF IMPLEMENTING THE BIOLOGICAL EOVS

Phytoplankton Biomass and Diversity and Zooplankton Biomass and Diversity

The plankton EOVs have been approached together as there is considerable overlap in expertise and monitoring networks. The scientific community has recognized the importance of understanding plankton abundance, diversity and productivity for centuries (Muller-Karger et al., 2014). Many of the ecosystem services supporting human activities in coastal and ocean waters depend on planktonic organisms, which represent the lowest trophic levels in the ocean and are key components of global biogeochemical cycles. Human pressures, direct and indirect, and natural variation in the Earth system, are having significant impacts on these sensitive biological assemblages. These changes can affect fisheries, the distribution and frequency of harmful algal blooms, affect the spatial distribution (range and timing) of different species and cause other shifts in marine habitats around the world. The abundance of many fish species, sea birds, and marine mammals on continental shelves is critically tied to fluctuations in the abundance of smaller planktonic organisms driven by climate-scale changes. On the other hand, changes in the grazing pressure by fish and zooplankton also have a marked influence on the diversity, abundance, and productivity of these microorganisms (Prowe et al., 2012). Many of these changes are impossible to detect without an observing system in place, or without an agreement on what to measure and how to make these measurements so that they can be compared from one location to another and over time.

Continuous Plankton Recorder (CPR) surveys exist in several ocean basins, with time series up to multiple decades, providing plankton diversity and distribution information. While not yet truly global, there are efforts underway to expand CPR surveys to other key areas and integrate with other observing systems (Batten et al., 2019). Measuring plankton distribution, biodiversity, abundance, productivity, and changes in these variables over time in the global ocean is impractical without agreement on best practices and strategies for integration with existing time series. GOOS now provides a framework to coordinate global, sustained and multidisciplinary observations of plankton. Under the GOOS, experts from across ocean disciplines have formulated recommendations for a multi-year implementation plan that addresses requirements, observations, data management, and information products for a sustainable plankton observing capability (Lombard et al., 2019).

Persistent challenges include spatial coverage and temporal resolution of plankton observations, observation technologies, and the need for standardized methods or Best Practices (Przeslawski et al., 2019). New automating technologies, such as imaging and ‘omics are increasing data collection opportunities, while machine learning processes and improved (real time) quality control will facilitate development of standardized outputs that can be harvested directly by major biodiversity databases such as OBIS and GBIF. At the same time, it will be necessary to carefully document the capabilities of new technologies and methods as complements or replacements for more traditional approaches. Pilot projects to test components of the implementation plan at local to regional scales involving imaging equipment such as the Underwater Vision Profiler (UVP), the Imaging Flow CytoBot (IFCB) or other automated systems on selected GO-SHIP lines or at fixed stations such as OceanSITES will be important in demonstrating the scalability of plankton observations to the global ocean (Miloslavich et al., 2018c).

Improved communication with all ocean stakeholders, including the public, policy makers, environmental managers, and industry, are essential to future development of this EOV. The public needs to understand the importance and impact of changes in plankton communities for the wellbeing of human populations and for ocean health. Sustaining the ecosystem services that plankton provide is crucial for the security of nations.

Fish Abundance and Distribution

Monitoring the spatial and temporal dynamics of fish is a basic requirement for their assessment under the impacts of climate change, fishing and pollution. Due to their global coverage, most indicators of change are based on commercial fisheries catch data. However, there are significant issues regarding accessibility of fisheries data and obligations of national reporting to the Food and Agricultural Organization of the United Nations (FAO). Multiple lines of evidence show the importance of fisheries independent data to provide reliable assessments of fish status in support of management decisions for an ecosystem approach to fisheries (Shin et al., 2012; Pauly et al., 2013; and see references in Miloslavich et al., 2018a). In addition, the status of many non-commercial fish, marine mammals, sea turtles and seabirds impacted by commercial or recreational fishing, pollution, habitat degradation and climate change, provide important information for ecosystem-based approaches to fisheries management.

Multispecies trawl survey data, pelagic acoustic survey data, tagging data, and underwater survey data are rich sources of information for coastal and offshore fish communities. These data are collected in many countries. In addition, less infrastructure-dependent approaches for coastal and continental shelf sites including citizen scientist diver surveys (Edgar and Stuart-Smith, 2014) and Baited Remote Underwater Video (BRUV, Hill et al., 2018) provide cost-effective approaches to sample shallow water fish communities.

New technologies expanding data collection opportunities are already in use or are under development including e-monitoring on fishing vessels, acoustic echosounders on fish aggregating devices (FADs) or gliders, sound monitoring, and environmental DNA. Midwater acoustic methods are being developed for monitoring the mesopelagic fish community (Proud et al., 2018). However, for most of these methods, spatial and taxonomic coverage remains narrow, and further development is required to automate and standardize the collection and analysis of data.

Unfortunately, data are rarely standardized or accessible. More initiatives are needed to make data open (e.g., Reef Life Survey; Edgar and Stuart-Smith, 2014), coordinated and quality controlled (e.g., DATRAS for trawl surveys in European seas[3]) and available for people to store data collected globally (e.g., OBIS or for BRUV data[4]). A first step in developing this EOV will be to inventory existing databases (metadata and metadata standards) around the world to identify opportunities and incentives to increase the availability of fisheries independent observations.

Secondly, strengthening the linkages between global and national indicator development and reporting, and demonstrating the utility of this EOV through use cases will support collaboration between multiple stakeholders, including the Convention on Biological Diversity (defining new targets for maintaining exploited ecosystems within safe limits), the Biodiversity Indicators Partnership (highlighting indicators for measuring progress in achieving targets), the UN Fisheries and Agriculture Organisation (leading national reporting), national fisheries departments (conducting primarily exploited fish surveys), national environmental departments (conducting primarily non-exploited fish surveys, including threatened species), scientific experts (through e.g., ICES and PICES working groups, CLIOTOP, INDISEAS), fishing industries, NGOs, and regional fisheries management organizations.

[3] http://www.ices.dk/marine-data/data-portals/Pages/DATRAS.aspx
[4] http://www.globalarchive.org

Turtles, Birds, and Mammals

Turtles, birds, and marine mammals are important components of marine foodwebs, often at the top, and with the potential to exert top down control on foodweb structure and composition (Estes et al., 2014, 2016; Roman et al., 2014; McCauley et al., 2015). They also play a previously unrecognized role in biogeochemical cycling, as their foraging activities transport macro and micro nutrients both horizontally and vertically (Roman et al., 2014; Doughty et al., 2016; Moss, 2017). The habitats of these marine vertebrates whether they are associated with feeding, breeding or migration all depend on climate driven oceanographic features (Briscoe et al., 2017). For example, migration and dispersal of sea turtles is highly correlated with surface currents (Girard et al., 2009; Tew Kai et al., 2009; Peckham et al., 2011) while seabird foraging and migration depend on oceanic wind patterns (Weimerskirch et al., 2000; Suryan et al., 2008; Weimerskirch et al., 2012; Gutowsky et al., 2014). Foraging is most efficient in highly productive regions where primary production is greatest (Tynan, 1998; Croll et al., 2005), or where prey is concentrated due to mesoscale features such as fronts, eddies and filaments (Bost et al., 2009; Hindell et al., 2016; Abrahms et al., 2018). Predictions of climate associated changes in their habitat suggest that there will be winners and losers (Hazen et al., 2013) with some climate driven changes in populations already being observed. (Ducklow et al., 2013; Boersma and Rebstock, 2014; Descamps et al., 2015; Thorne et al., 2016).

As "charismatic megafauna" these organisms have high societal value. Considerable resources go into their conservation and management (Moore et al., 2009; Wallace et al., 2011; Lewison et al., 2013; Borggaard et al., 2017; Lent and Squires, 2017) as well as methods to monitor their populations (Southwell et al., 2012; Battaile and Trites, 2013; Desprez et al., 2013; Hatfield, 2013; Kirkman et al., 2013; Moore and Barlow, 2013). Populations of many of these species have been monitored for decades (Rotella et al., 2012; Pardo et al., 2017; Southwell et al., 2017; Tompkins et al., 2017; Weimerskirch et al., 2018), but many different methods are employed to estimate key variables such as population size, demographic changes, body condition and movement patterns. Very little of the resulting data are compiled in a common repository. Monitoring of these populations also involves solving logistical challenges. For example, Cetaceans are a logistically difficult group to monitor, as they spend their entire lives at sea and to monitor, survey or capture them requires considerable effort. While, the logistics associated with assessing populations, animal condition, movement patterns and diet for colony breeding sea turtles, seabirds, and pinnipeds have been well established, some species and populations may be difficult to access due to their remote location or cryptic nesting habitat such as burrowing seabirds.

Although significant time-series exist for many marine vertebrates, the data have not been collected in a common repository so in most cases they are not accessible while in others even their existence is poorly known. A significant step forward, and a goal for GOOS over the next few years, will be to develop a data portal to identify existing data sets and who manages them, with a goal to eventually provide direct access to the data. This will require bringing together the various communities collecting and using the data to identify or establish best practices for data collection, analyses, maintenance, and archiving. The most successful program pursuing best practices to date has been the CCAMLR Ecosystem Monitoring Program or CEMP (Reid et al., 2005; Constable, 2011). This program developed a series of metrics that can be used to follow the status and condition of species of seabirds and marine mammals that are krill predators. CEMP established a detailed series of metrics that have been used to monitor krill-eating birds and mammals.

Our aim over the next 5 years is to focus on each taxa, identify existing networks collecting data on their abundance and distribution through various methods and engage the communities to refine and agree to best practices as observations are brought together and made available globally.

Hard Coral Cover and Composition

Coral reefs are under significant direct pressure from human activities in the form of fishing, pollution, recreation, transport and coastal development, and are especially vulnerable to the global threats of ocean warming and acidification (Burke et al., 2011; Hughes et al., 2017). Recent analyses indicate that most coral reefs will not survive the next 3–5 decades unless the most ambitious climate mitigation targets are met (van Hooidonk et al., 2016; Beyer et al., 2018), or they can ecologically adapt. The importance for developing sustained global observing is highlighted by the IPCC report on 1.5°C warming, in which the difference between 1.5° and 2°C warming is illustrated by losing nearly all, versus losing all, coral reefs globally by the end of this century (Intergovernmental Panel on Climate Change, 2018).

Given the high vulnerability and value of coral reefs, establishing local to global long-term monitoring of the health and drivers of coral reefs is of paramount importance (GCRMN, 2017; Miloslavich et al., 2018a), and has been a priority of the International Coral Reef Initiative for 20 years or since the 1st global coral bleaching event of 1997–98 (e.g., Wilkinson, 2000, 2008). Recent guidance from both GOOS (Lindstrom et al., 2012) and GEOBON (Pereira et al., 2013) on establishing global observing networks provided key inputs to a redesigned global observing network for coral reefs, in the form of the GCRMN (2018), including an expanding the scope to integrate socioeconomic and biophysical elements. Key redesign elements include: (1) network design applying the principles of the Framework for Ocean Observations (Lindstrom et al., 2012 p. 7); (2) applying the Drivers Pressures Status Impact Responses (DPSIR) model used in many convention processes (Patricio et al., 2016; Miloslavich et al., 2018a); (3) adopting the EOV/EBV frameworks (Muller-Karger et al., 2018b) to identify the priority variables for understanding and reporting on the health of coral reefs; and (4) an integrated monitoring/adaptive management approach to ensure local-level management can respond to pressures, trends and capacity.

A GOOS/GCRMN hard coral cover and composition EOV workshop was held in Dar es Salaam, Tanzania in November 2017 with the support of IOC, the International Coral Reef

Initiative (ICRI), and UN Environment[5]. A governance plan to strengthen the GCRMN based on the discussions of this workshop and two more workshops organized by the UN Environment was adopted in December 2018 by the International Coral Reef Initiative (GCRMN, 2018).

Seagrass Cover and Composition

The dominant primary producers on sedimentary shores around the world are seagrasses, which provide habitat structure and food for diverse and abundant animal communities and are hotspots of ecosystem and biogeochemical processes. Seagrass meadows are economically central to coastal human communities, particularly in the developing world, contributing to fisheries yield, storm protection, blue carbon storage, and important cultural values (Nordlund et al., 2016; Unsworth et al., 2018).

Recent assessments of global seagrass status and trends show substantial loss of seagrass over recent decades threatening the services provided by these ecosystems (Waycott et al., 2009; Grech et al., 2012). The principle drivers of change in seagrass cover on a global scale are urban and industrial runoff, urban and port infrastructure development, agricultural runoff, and dredging (Grech et al., 2012). Tracking status and trends in seagrass cover and quality is therefore widely recognized as a priority for coastal management, and seagrass is monitored at numerous sites worldwide.

In 2018, researchers and managers from around the world drafted a consensus assessment and recommendations on the current state of, and opportunities for, advancing global marine macrophyte observations, integrating contributions from a community with broad geographic and disciplinary expertise (Duffy et al., 2019). This review noted that several challenges hinder effective global observing of seagrass status and trends. Central among these is lack of coordination among the numerous seagrass monitoring programs, which in turn is hindered by wide variance in their goals, methodologies, and data availability. A second major challenge is the difficulty of quantifying seagrass cover and distribution with remote sensing as is done routinely for phytoplankton biomass and, increasingly, for coral reef cover.

Based on review of 19 active, multi-site seagrass monitoring programs and many more local efforts, the consensus assessment made several main recommendations: a coordinated seagrass observing system will best be built by: (1) harmonizing observations and best practices developed by existing networks; (2) identifying a core set of common metrics and a common hierarchical sampling design; (3) actively promoting common standards for taxonomy, data management, and governance; and (4) active capacity building. The group also recognized strong potential for advancing coordinated observations of seagrass ecosystems by more closely integrating existing *in situ* surveys with remote sensing imagery and incorporating environmental DNA and metagenomic approaches for sampling taxa difficult to assess by traditional sampling. Realizing these recommendations will produce more effective, efficient, and responsive observing, a more accurate global picture of change in seagrass systems, and stronger international capacity for sustaining observations. The consensus among global seagrass researchers indicates that the community is engaged and committed to moving these goals forward. These efforts are continuing through an ongoing assessment led by the International Seagrass Experts Network and UNEP/GRID-Arendal.

Macroalgal Canopy Cover and Composition

Macroalgal forests are iconic on rocky shores around the world's coasts. These highly productive and diverse ecosystems provide many important functions and services including provision of nursery areas, human food resources, and protection from coastal erosion. Macroalgal forests and the associated assemblages are vulnerable to global threats such as ocean warming and acidification, and to regional anthropogenically mediated stressors including habitat degradation, eutrophication, other pollution, over-fishing, and invasive species. Due to their sensitivity to a variety of stressors, macroalgal forests are indicators of the status and trends of marine coastal ecosystems worldwide.

To develop a global, coordinated strategy for monitoring macroalgal forests, the Partnership for the Observation of the Global Ocean (POGO) supported a Working Group (WG) of international, multidisciplinary experts to plan the implementation of a standardized, innovative and cost-effective monitoring system. The WG compiled metadata of more than 80 existing programs operating from local to global scales, identifying the strengths of these efforts in addition to the gaps and requirements to achieve global standardization. The WG also reviewed the methods available to monitor macroalgal forests, including visual census, acoustics, laser imaging, remote sensing from satellites, molecular tools (including environmental DNA), and imagery (stills, automated/remote vehicles, drones). The strength and weaknesses of the different methodologies were evaluated and compared with respect to feasibility, training requirements, spatial scale of analysis and taxonomic resolution. A fit-for-purpose Standard Operating Procedure (SOP) is being drafted for each of the different methodological approaches. The requirements for data integration, assimilation and dissemination were discussed and a data management architecture was proposed to provide a centralized repository linked with OBIS under the principles of "Findable, Accessible, Interoperable, and Re-useable" (FAIR) data.

Persistent limitations hampering the implementation of a global monitoring network for macroalgal forests include the harmonization of data originated by different technologies, the adoption of common protocols and the use of standardized vocabularies. Sampling designs should reflect clearly stated questions and hypotheses about the drivers of change in macroalgal forests at local, regional and global scales. Clarification of the relevant questions beforehand will facilitate the adoption of common designs and data integration, also allowing more powerful analyses. Adequate resources need to be made available to guarantee the long-term commitment of a global network.

[5]Summary and recommendations at: http://www.goosocean.org/index.php?option=com_oe&task=viewDocumentRecord&docID=20794.

The POGO-supported working group defined a strategic implementation plan to address these challenges and to promote macroalgal canopy cover and composition as an EOV, including: (1) formalize a data request template and data sharing agreement to compile a comprehensive inventory of existing datasets; (2) finalize the SOPs for the different methodological approaches to be made available through the Ocean Best Practices platform; (3) develop vocabularies, non-taxonomic categories and units for recorded variables; and (4) improve communication and dissemination through papers, presentations, training material and websites. The vision is to integrate macroalgal canopy cover and composition into a global observing network and to promote this EOV as a leading indicator of the status and trends of macroalgal forests worldwide.

Mangrove Cover

Found in the coastal zones across the tropics, subtropics and temperate regions, mangroves are forested wetlands that are uniquely adapted to the intertidal zone. Although mangroves provide many critical resources to local populations, including food and timber, their extent has been reduced over recent decades, and many habitats have been fragmented or degraded (FAO, 2008; Romanach et al., 2018). Changes in the distribution of mangroves have gone largely unrecorded and many areas have been permanently or temporarily lost primarily due to human activities. The lack of monitoring and assessment at country, regional and global scales has often led to losses not being recognized, while impacts of losses on the integrity of ecosystems have rarely been quantified. However, increasing efforts are now being made to both protect and restore mangroves. A fundamental requirement for mangrove protection and restoration is to understand current and historical mangrove distributions and condition (Bunting et al., 2018).

Sustained measurements of mangrove cover and composition are necessary to assess the state and change of these ecosystems, address scientific and societal questions and needs, leading to information to help mitigate pressures on mangroves at local, regional and global scales. While various platforms exist, few provide consistent and sustained observations of both mangrove cover and composition beyond the national scale. The scientific community has been active in both addressing the gaps in information on global mangrove cover and in identifying opportunities for restoration. Through the Global Mangrove Watch, an international project set up to provide geospatial information about mangrove extent and changes, a time-series of maps of the global mangrove extent was generated and released in 2018. Including a baseline showing the global extent of mangroves in 2010, maps are currently available for seven annual epochs including 1996, 2007, 2008, 2009, 2015, and 2016 from which losses and gains in any location can be assessed (Bunting et al., 2018). These data provide the information needed to report at the national level on mangrove extent to the Ramsar Convention and the Sustainable Development Goals (6 and 14 in particular), as well as Nationally Determined Contributions under the Paris Agreement and the UN Reducing Emissions from Deforestation and forest Degradation scheme (REDD+) under the UN Framework Convention on Climate Change (UNFCCC). The Global Mangrove Alliance is working to develop a mangrove monitoring system to track progress toward their restoration target of 20% of mangroves globally by 2030.

While these platforms address the previous information gap on mangrove extent, data are still lacking on mangrove species distribution and habitat type. Determining the characteristics and composition of mangroves requires more detailed site level information. In some locations this information is provided through national mangrove monitoring systems (e.g., Mexico and Australia), but the existence of national level systems is often constrained by financial and staff resources and they are not common globally. Even in Australia it took over 6 months before the loss of over 1,000km of mangroves was noticed by scientists or authorities (Duke et al., 2017).

An inventory of existing databases will be the first step in identifying best approaches for addressing EOV requirements. The implementation plan for this EOV will include: (1) assessing the maturity of measurements; (2) coordinating observations; and (3) identifying appropriate data standards and management approaches. A workshop is scheduled in June 2019 to develop the mangrove (and seagrass) EOVs.

Microbial Biomass and Biodiversity

The ocean microbiome plays a central role in the state and functioning of the entire marine realm, its biogeochemical cycles, and the health of its flora and fauna (Moran, 2015; Hutchins et al., 2017). Consequently, the marine microbiome rapidly responds to natural and anthropogenic pressures, offering a rich source of largely untapped bioindicators of phenomena including invasive species, the presence of pathogens and environmental contaminants, and ecosystem resilience [see Buttigieg et al. (2018) and Bourlat et al. (2013), for commentary). As global capacity and drive to monitor environmental microbiomes grow (Dubilier et al., 2015; Goodwin et al., 2017; Thompson et al., 2017), the GOOS BioEco panel has recognized the need to develop an EOV reporting on microbial biomass and diversity in the oceans. Microbial life constitutes a notable proportion of Earth's total biomass, particularly in the form of bacterial biomass in the subsurface (including subseafloor sediments and the oceanic crust) (Kallmeyer et al., 2012; Bar-On et al., 2018). Monitoring microbial biomass is key to understanding the biogeochemical dynamics of ecosystem-defining events such as cyanobacterial blooms, their remineralization, and associated oxygen consumption during material export to the deep. The second component of this EOV addresses the immense and deeply minable functional and phylogenetic diversity of microbial assemblages. Rapidly advancing and increasingly affordable molecular profiling technologies, remote sampling solutions, and ecogenomic sensors (McQuillan and Robidart, 2017; Scholin et al., 2017) have greatly increased the feasibility of routinely assessing microbial biodiversity and have been refined over a decade of large-scale marine sampling campaigns (e.g., Rusch et al., 2007; Kopf et al., 2015; Sunagawa et al., 2015; Biller et al., 2018). These factors, bolstered by experience from methodological intercomparisons (e.g., Pesant et al., 2017; Sczyrba et al., 2017), are increasing the deployability of "omics" technologies within global frameworks of biodiversity and ocean assessment (Bruford et al., 2017; Buttigieg et al., 2018; for more on omics in biodiversity monitoring, consult Canonico et al., this issue). Harmonization and standards are increasingly necessary to achieve large scale analysis of the increasing data volumes being generated from "omics" technologies.

In consultation with a growing group of experts, we are working toward the first release of the Microbial Biomass and Biodiversity EOV's GOOS specification sheet. The initial scoping of the EOV will focus on bacterial and archaeal life; however, the viral and eukaryotic components of the microbiome will also be considered as our expert group grows. Microbial observatories federated through thematic networks such as the Global Omics Observatory Network (GLOMICON)[6] and the Genomic Observatories (GOs) Network (Davies et al., 2014) will be instrumental in this endeavor, as will information infrastructures such as the International Nucleotide Sequence Database Collaboration (INSDC), GBIF (2018)[7], and OBIS[8]. Multiple workshops over 2018 and 2019 have connected these entities to the Microbial EOV, as well as the IOC-UNESCO Ocean Best Practice System (OPBS; Pearlman et al., this issue)[9] and the Genomic Standards Consortium (GSC)[10]. The conclusion of the 21st meeting of the GSC (May 2019; Vienna) has resulted in the strategic alignment of GLOMICON and the GOs Network around the production of data products such as this EOV, significantly enhancing its prospects for advancement over the next three to 5 years.

There are several key challenges in the mainstreaming of microbial observation. On a conceptual level, we recognize that this EOV must be disaggregated as the scale of the "microbial" world spans several orders of magnitude. Eukaryotic, archaeal, bacterial, and viral sub-variables must be defined, each one led by domain experts nested within the core EOV. Further, the overlap and complementarity of this EOV – in theory and practice – with the Phyto- and Zooplankton EOVs must be carefully considered, likely leading to overlapping data products and communities of practice. Next, the considerable challenge of harmonizing and operationalizing global practices and promoting data sharing in a quickly developing and competitive field will require a great deal of coordination and meaningful incentivization to ensure interoperability from field sampling to data product creation. Anticipating ever-increasing technological capacity, long-term sample archiving to support decadal re-sequencing and analysis must be concretized through organizations such as the Global Genome Biodiversity Network (GGBN)[11]. As a corollary of sampling valuable biomaterial, microbial observers must also address the challenge of navigating and complying with international biodiversity legislation such as the Nagoya Protocol and the emerging legal agreements on biodiversity of the high seas under the UN Convention on the Law of the Sea. Lastly, sustainable resourcing of the practices chosen to measure this EOV (which may vary from local methods) must be secured by multiple partners in variable funding environments and bolstered by capacity sharing strategies (e.g., regional or project-based sequencing, regional sample archiving) where appropriate.

While the challenges are formidable, they are far outweighed by the great opportunity of augmenting biological observation with microbial insight. In addition to the integration and implementation common to other EOVs, we recommend: the development and use of physical calibration standards (e.g., "mock communities") and reference samples to enhance comparability between laboratories; the systematic development and testing of novel microbial bioindicators for ecosystem state and health, and; engaging with sensor and sampling hardware developers to ensure mutual alignment with EOV specifications.

[6]http://www.glomicon.org
[7]http://www.gbif.org
[8]https://obis.org/
[9]http://www.oceanbestpractices.org
[10]http://gensc.org
[11]http://www.ggbn.org

Supporting EOVs (Additional to Existing Physical and Biogeochemical EOVs)

Ocean Sound

Sound propagates so well in the ocean that it is the most effective way to probe the marine environment and communicate over long distances. Sound is critical for marine life and for seagoing humans. Many marine animals produce sound and acoustic cues are essential for larvae to settle in appropriate environments, for the mating systems of many fish and mammals, for predator-prey relationships, and for social species to maintain cohesion. Most fish and invertebrates sense sound-induced particle movement; some fish and all mammals detect changes in sound pressure, and the primary variables for Ocean Sound are time series of these two components of sound. However, the primary uses of the Ocean Sound EOV are biological and ecological.

The Ocean Sound EOV will forge major advances in our understanding of how acoustic monitoring can be used to assess biodiversity and ecosystem health, how different sources of anthropogenic sound affect ocean ambient (or background sound), and the effects sound has on marine life. We know that anthropogenic noise can harm marine life in the short term, but more extended observations are required to define long-term effects on populations and ecosystems. Understanding the potential for ocean noise as a stressor requires (1) estimating how ocean sound has changed historically, (2) mapping sound throughout the oceans on a global scale over decades, and (3) predicting sound fields that result from changes in the use of the oceans. Impacts will be taxa-specific.

The Ocean Sound EOV will be implemented under auspices of International Quiet Ocean Experiment (IQOE) which is under governance from SCOR (Scientific Committee on Oceanic Research) and POGO (Partnership for Observation of Global Oceans). The specification sheet for Ocean Sound was drafted in 2016–2017 by an IQOE Working Group funded by POGO and revised in response to review by the GOOS BioEco panel during the fall of 2017 and spring of 2018. It was approved by GOOS during the summer of 2018. The Ocean Sound EOV has been presented to scientific stakeholders at the Joint American and European Societies for Acoustics in Boston June 2017. Engagement with non-scientific stakeholders included the Comprehensive Test Ban Treaty Organisation, International

Maritime Organisation among international organisations, and US agencies including the NOAA Ocean Noise Strategy Group, US Office of Naval Research, and Bureau of Ocean Energy Management. Presentations were given at the World Ocean Council in Halifax, Nova Scotia, Canada, November 2017, at the United Nations Open-ended Informal Consultative Process on Oceans and the Law of the Sea in New York, June 2018, and the US Sub-committee on Ocean Science and Technology (SOST) known as the "Ocean Noise and Marine Life Task Force" in Washington DC, August 2018. Future efforts to develop the implementation plan include emailing the EOV spec sheet for review and input, a workshop scheduled for spring 2019 and a session before or after OceanObs'19.

Marine Debris

Marine debris is both widespread in the marine environment (Eriksen et al., 2014) and has significant ecological, social and economic impacts. Plastics form a large and enduring proportion of marine debris, and many governments and communities throughout the world are implementing policies to reduce the amount of plastics entering the marine environment. Plastics also degrade extremely slowly in the open ocean leading to local accumulations and the passage of plastics to the deepest parts of the world ocean. Despite increasing attention in recent years, the impact of plastic litter in the oceans remains uncertain and remains a key objective of the Group of Experts on the Scientific Aspects of Marine Environmental Pollution (GESAMP) Working Group #40[12].

This working group is developing guidelines for sampling and analysing marine macro-plastics and microplastics, including: defining the size and shape of particles; sampling protocols for surface and sub-surface seawater, seabed sediments, shorelines and biota; and, physical and chemical identification and analysis of polymers and associated chemicals requirements for monitoring and assessment. The GOOS Biology and Ecosystems Panel will be collaborating with this working group to support the development and uptake of these guidelines.

Ocean Color

The term "ocean color" broadly refers to the spectral radiance emanating from the sun that is backscattered off the upper part of the oceanic water column, and which contains information on the properties of the water and its constituents. The phenomenon of color is the result of absorption and scattering, as light interacts with the water and materials suspended or dissolved within it (i.e., the optically active "constituents"). Ocean color encompasses a multitude of biological, biogeochemical, and ecological properties of the ocean, and is an EOV and ECV because changes in the color of the ocean can be related to changes in the presence and magnitude of living and non-living particles and of dissolved materials in the water. Ocean color can be used to discriminate different water bodies, evaluate the health of marine ecosystems, and inform resource management, e.g., aquaculture, fisheries and recreation and provides an example of how other biological EOVs might be implemented.

Measurements of ocean color include the intensity and spectral variability of light backscattered from below the ocean surface, vertical profiles of the color of water, and measures of inherent optical properties like the absorption or scattering coefficient. Current methods to observe the ocean's optical properties include underwater optical sensors as well as airborne and satellite observations. Sustained ocean color remote sensing observations are obtained routinely from polar-orbiting and geostationary satellites, AERONET-OC stations, and airborne sensors. Ships, buoys, and automated platforms, including gliders, Argo floats, and other various specialized sensors deployed at various sites, including validation sites, provide complementary in-water optical observations which are used to calibrate on-orbit satellite sensors and validate remotely sensed data products.

To fully use the ocean's optical properties for ocean science, it is critical to understand the properties of different water types, and the limitations and possible errors in derived "ocean color products." Products include phytoplankton chlorophyll *a* concentration, biogeochemical and ecological indices including water quality measures, metrics to gauge phytoplankton physiology, and indicators of ecosystem status and health. Environmental variables such as bathymetry, dissolved organic carbon, and suspended sediment concentration can be derived and will often need to be accounted for before biological components can be estimated. *In situ* sampling is required to validate remotely sensed products.

To date, ocean color sensors have focused on measuring in the visible spectrum of light including PAR (Photosynthetically Available Radiation, or between 400 and 700 nm). However, there is a clear need for ocean color sensors to observe from the ultraviolet (UV) to the short-wave infrared (SWIR), with high spectral resolution (hyperspectral), and with more sensitive sensors (signal to noise) to enable more precise atmospheric correction over turbid waters, as well as to enable development of new products and revision of existing products, including suspended and dissolved matter in turbid waters, bathymetry, plankton functional types, and other products. Applications in coastal and inland waters require higher spatial resolution (i.e., pixels of order of meters to tens of meters) than open ocean assessments (spatial resolution of hundreds of meters to kilometers).

Links to Other Essential Variable Initiatives

No one group has the imprimatur to identify a set of oceanographic variables that all other researchers would be expected to measure and record. Improving general acceptance of Essential Variable initiatives requires demonstrating that there is value in this process, e.g., through the improved interpretation of individual project data, or improved impact of data when it is aggregated and assessed more broadly for science or decision-making. It is important in this regard that Essential Variable initiatives collaborate to provide a clear and consistent message to the scientific community. The Essential Climate Variables (ECVs) started in this way in the 1990's and now provide fundamental information to inform negotiations under the United Nations

[12]http://www.gesamp.org/work/groups/40

Framework Convention on Climate Change (UNFCCC) and the Intergovernmental Panel on Climate Change (IPCC).

The three main groups that the Biology and Ecosystems Panel engages with are: Global Climate Observing System (GCOS), the Marine Biodiversity Observation Network (MBON) and the Ocean Biogeographic Information System (OBIS). Many other groups are accessed through these three groups including the joint representation of individuals on different groups (Muller-Karger et al., 2018b).

Essential Climate Variables

The Global Climate Observing System (GCOS) has addressed climate-related needs for observations and information since 1992, under the umbrella of four major intergovernmental organizations[13]. GCOS operates through three panels focussed on atmospheric, ocean, and terrestrial observations. The agreed Essential Climate Variables (ECVs) are relevant to the requirements of the UNFCCC and other stakeholders. The new GCOS Implementation Plan (World Meteorological Organization [WMO], 2016) has a focus on closing the climate cycles – Hydrological, Carbon and Cryosphere – by ensuring global observations for adaptation, mitigation and climate indicators. This new plan also considers for the first time biological ECVs related to ocean observations and proposes a series of actions to improve their data delivery (**Table 2**). The GOOS Biology and Ecosystems Panel worked with GCOS to identify biological ocean ECVs based on the EOVs which in this first iteration are Plankton including both phyto and zooplankton, and Marine Habitat Properties which includes coral reefs, seagrass beds, mangrove forests and macroalgal canopies (**Table 2**).

[13]https://public.wmo.int/en/programmes/global-climate-observing-system

TABLE 2 | Main actions proposed by the GCOS Implementation Plan in relation to the biological ocean ECVs (World Meteorological Organization [WMO], 2016).

ECV	Actions
Phytoplankton	Improve the conversion of satellite observations to phytoplankton biomass; implement *in situ* monitoring along with other relevant physical and biogeochemical variables
Zooplankton	Implement global CPR surveys expanding to new areas (e.g., tropical and subtropical); integrate data
Coral reefs	Strengthen existing network of coral reef monitoring sites and encourage collection of other relevant physical, biogeochemical, biological and ecological measurements; encourage the use of inter-calibrated protocols and implementing capacity development
Mangrove forests, seagrass beds and macroalgal communities	Advance establishment of global monitoring networks for seagrass, mangroves and macroalgae and encourage collection of other relevant physical, biogeochemical, biological and ecological measurements; encourage the use of inter-calibrated protocols and develop capacity

Essential Biological Variables

Essential Biodiversity Variables (EBVs) were defined by the Group on Earth Observations (Pereira et al., 2013) and are complementary to the biological EOVs developed by GOOS. While the biological EOVs are strictly organized around species and habitats, the EBVs also include biological processes. Some EBVs are consistent with supporting variables under the EOVs, while some EOVs are examples under an EBV class. While there is not a one to one relationship or strict hierarchy linking the biological EOVs and EBVs, they will often be monitoring the same aspects of the marine environment.

The Marine Biodiversity Observation Network (MBON), a thematic component of GEO BON, is collaborating with GOOS, the Ocean Biogeographic Information System (OBIS), and the Integrated Marine Biosphere Research (IMBeR) project to ensure that EBVs and EOVs are complementary, representing alternative uses of a common set of scientific measurements (Muller-Karger et al., 2018b).

Characterizing biodiversity and understanding its drivers will require incorporating observations from traditional and molecular taxonomy, animal tagging and tracking efforts, ocean biogeochemistry, and ocean observatory initiatives including the deep ocean and seafloor. The partnership between large-scale ocean observing and product distribution initiatives (MBON, OBIS, JCOMM, and GOOS) is an expedited, effective way to support international policy-level assessments (e.g., the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services or IPBES), along with the implementation of international development goals (e.g., the United Nations Sustainable Development Goals).

Ocean Biogeographic Information System

OBIS is a global open-access data and information clearing-house on marine biodiversity for science, conservation and sustainable development. For almost 20 years now, OBIS and its 30 regional OBIS nodes have been successful in mobilizing a global network of nearly 1,000 institutions to provide seamless, integrated access to nearly 60 million records of 120,000 marine species. Since 2017, OBIS expanded from focussing purely on species occurrence data to embrace datasets that combine biological and environmental data, including details about sampling effort and methods, and supporting EOVs, EBvs and ECVs (De Pooter et al., 2017; Benson et al., 2018). Its new infrastructure (OBIS 2.0) supports robust near real-time data integration and curation and provides powerful data access and analytical services.

A major challenge is that many biological EOV data are fragmented, lack standardization, are not archived, and many remain unavailable. Consequently, very few monitoring networks are currently capable of developing global indicators to feed into policy frameworks, excepting the Continuous Plankton Recorder, which provides indicators for the EU Marine Strategy Framework Directive. Alignment with DarwinCore standards and feeding EOV data into OBIS is a goal for each EOV. Tracking networks which are developing data and metadata guidelines together with OBIS and the Bio-logging Society Good is one example of progress.

By applying Darwin Core standards to the EOV data (more specifically the Event Core and Measurement or Fact), OBIS will be able to support GOOS in mapping and monitoring the marine biological observing networks globally.

ORGANIZATIONAL STRUCTURE AND CHALLENGES

The GOOS Biology and Ecosystems Panel reports to the GOOS Scientific Steering Committee, which reports to the Intergovernmental Oceanographic Commission of UNESCO (IOC) Assembly and other sponsors. GOOS was established in 1991 by IOC Member States, with the World Meteorological Organization, UN Environment, and the International Science Council later joining as sponsors.

The Framework for Ocean Observing (Lindstrom et al., 2012) developed from OceanObs'09 recommended establishing two new GOOS Panels – Biogeochemistry, and Biology and Ecosystems – to complement the existing Physics and Climate Panel. This recommendation was endorsed by IOC in 2012. However, endorsement did not result in increased IOC budgetary support. While the Physics Panel is co-sponsored by the Ocean Observations Panel for Climate and the Biogeochemistry Panel builds on the International Ocean Carbon Coordination Project, there was no similar global monitoring group for the Biology and Ecosystems Panel to build on, and it has been primarily supported by short-term research grants from individual research agencies in Australia and the United States.

At the same time, GOOS is not the only group interested in monitoring ocean biota. GOOS is in communication with other groups including MBON, the Southern Ocean Observing System (SOOS) and Integrated Marine Biosphere Research [IMBER; including the Climate Impacts on Ocean Top Predators (CLIOTOP) and Integrating Climate and Ecosystem Data (ICED) programs), while groups likely to use the data for further processing include GEO BluePlanet, World Ocean Council, GODAE OceanView. Engagement with FAO, Regional Fishery Management Organizations (RFMO), UN Regional Seas Programs, the International Council for the Exploration of the Sea (ICES), the Pacific ICES (PICES) needs to be expanded. Many, if not all, of these groups are underfunded and rely heavily on voluntary commitments. There is an ever-increasing need for a global inclusive architecture that can support the needs of all these groups.

The other dimension of GOOS is the 13 GOOS Regional Alliances (GRAs) that enable regional cooperation in ocean observing and in some cases in ocean forecasting and services. However, biological monitoring is not included in some GRAs and there is generally a lack of capacity in the developing world. Building an operational system that is truly global requires expanding participation to include a far broader representation of developing and less-resourced countries. Current capacity development activities are insufficient. New stronger partnerships, new funding models, innovative technologies and new training approaches will be required (Miloslavich et al., 2018b). Linking capacity development to sustained monitoring may be one way to provide long-term effectiveness for both (Bax et al., 2018).

Continuing funding of the GOOS Biology and Ecosystems Panel remains a challenge. The first 3 years of the Panel have had clear scientific aims and outputs, requiring intellectual rather than more tangible investment. Scientific individuals and institutions have the capacity and interest in contributing to endeavors such as GOOS with clear timely deliverables including scientific publications and profile. It may be harder to maintain investment for the longer-term support and coordination of a sustained observing system, especially for research agencies and universities, despite there being so many international frameworks and conventions that would profit from the resulting increased information (**Figure 3**).

There are high expectations for IOC, given its position as the only UN agency with a mandated role for ocean science, and its role in defining capacity development and technology transfer requirements. These expectations have been raised for example at the negotiations under the UN Convention of the Law of the Sea over a new instrument for the conservation and sustainable use of marine biodiversity beyond national jurisdiction, but the IOC will need to identify additional stable funding opportunities if it is to reach its potential, increase collaboration with other relevant organisations, and support its programs including GOOS.

The development and implementation of a global ocean observing system that incorporates biological essential ocean variables is an explicit objective of the UN Decade. A sustained observing system would specifically contribute to several of the Decade's objectives by: (1) supporting an inventory of ocean resources to enhance their sustainable use; (2) expanding data gathering and data management to help forecasting of ocean food productivity; (3) improving baselines of environmental conditions of coastal ecosystems; (4) increasing scientific knowledge about the impacts of ocean warming, acidification and habitat destruction; and (5) promoting integrated observations and data sharing that are achievable and feed into GOOS.

However, one of the main governance impediments to the development of a global ocean observing system may be the lack of a clear reporting structure. As Banks (2018) stated while reviewing the lack of success of Evidence Based Decision Making since its inception 20 years ago:

> *"But the main obstacle to using evidence in policy development is not so much lack of (potential) supply as lack of demand. Remedying this will necessitate in-depth consideration of governance and other arrangements that shape incentives and the relationship between ministers, advisers and departments."* (Banks, 2018)

There is clear relevance of the information developed from monitoring the EOVs at national, regional and international level (**Figure 4**), but without improved governance arrangements there may be few incentives to coordinate and improve delivery of scientific information to decision makers, and little incentive

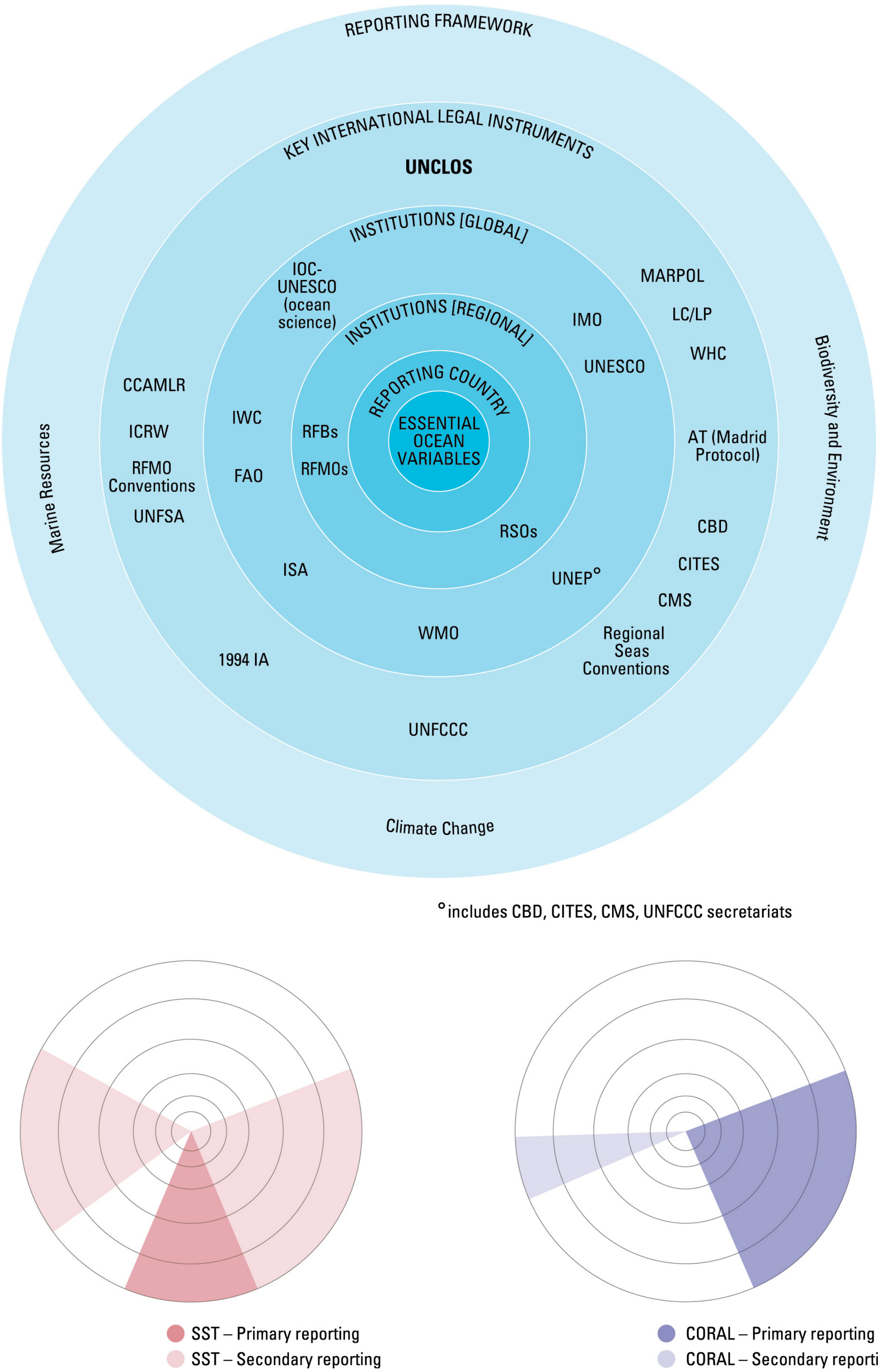

FIGURE 4 | An illustration of the many international instruments, legal instruments, and reporting frameworks that the GOOS EOVs deliver to. The smaller plots indicate the primary and secondary delivery areas for the sea surface temperature and coral cover and health EOVs (from Bax et al., 2018).

for researchers to modify current project-level priorities to contribute globally.

FUTURE DIRECTIONS AND DEVELOPMENTS

The advent of a recently expanded set of EOVs, including those focussed on biology and ecosystems coincides with important technological developments in areas of remote and automated data collection, automated image analysis, open data, data management systems, web mapping services, and biodiversity prediction modeling to name a few. Bringing these developments together in a focussed way can provide invaluable data and mapping products useful for research, marine spatial planning, policy development, and environmental regulation (**Figure 5**).

There are many exciting technologies under development that lend themselves to routine, operational monitoring of marine populations and habitats, including improved platforms, sensors, data analysis and processing. For example, passive acoustics has been used to monitor the presence and movement patterns of species that vocalize (Hildebrand et al., 2015; MacIntyre et al., 2015; Širovic et al., 2015; Munger et al., 2016; Kusel et al., 2017). Satellite images have been used to locate seabird and seal colonies and assess their population numbers (LaRue et al., 2011; Trathan et al., 2011; Fretwell et al., 2012, 2014, 2015, 2017; LaRue et al., 2017), whales at sea (Cubaynes et al., 2018), plankton functional groups and structured benthic habitats (Muller-Karger et al., 2018a). Small easily deployed drones or unmanned aerial systems have been used to assess populations as well as provide estates of body size and condition of marine vertebrates (Goebel et al., 2015; Christiansen et al., 2016; Krause et al., 2017), and may provide an intermediate step in linking satellite data to *in situ* verification for mapping coastal habitats including mangroves and seagrass. Under the water, autonomous underwater vehicles (AUVs) can now fulfill a monitoring role that previously required ship time and their capacity to include additional sensors and improve energy management are only going to increase (Hill et al., 2014; Monk et al., 2018). Meanwhile as costs drop, the feasibility of deploying multiple or even fleets of AUVs of different size will increase steadily. Finally, electronic tags are a mature technology that is being used to track the movement patterns, fisheries interactions, habitat utilization and distribution of marine organisms on a global scale (Costa et al., 2010; Block et al., 2011; Costa et al., 2012; Hussey et al., 2015; Brodie et al., 2018; Harrison et al., 2018; Sequeira et al., 2018; Harcourt et al., 2019). Furthermore, electronic tags carried by marine vertebrates have proven to be an extremely effective method for collecting high resolution oceanographic data such as temperature, salinity, and chlorophyll profiles in regions that are difficult, if not impossible (under polar ice) to sample, with other means (see Roquet et al., 2014; Treasure et al., 2017; Harcourt et al., 2019).

New platforms and sensors are leading to a massive increase in samples, including imagery, which will require automated processing to turn into useable data (**Figure 5**). Automated image processing for marine organisms ranging in size from the smallest plankton to larger vertebrates has been developing over at least the last 30 years but it remains a challenging area. Some areas, for example recognition of plankton, are sufficiently mature that sensors are now commercially available for field use (Boss et al., 2018), while areas like habitat assessment, e.g., of coral reef habitat, are developing rapidly (Roelfsema et al., 2018) and are limited in some cases by human consistency in habitat classification. Other areas such as recognition of fish species in a non-controlled environment, such as might be found during retrieval of a long-line, are proving more challenging. In each of these cases, the automation of easily and relatively cheaply collected image data has the potential

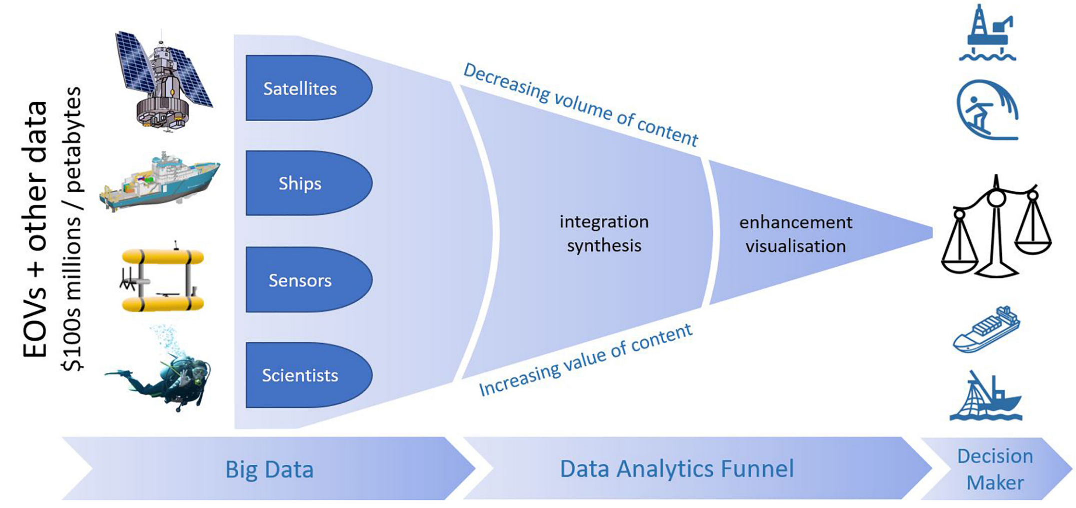

FIGURE 5 | Schematic of "data funnel" able to synthesize EOVs and other large data holdings in a form readily usable by decision makers and scientists. While the endpoint is "data products at finger tips," this kind of system needs to make the underlying data readily findable and accessible from the data product. Seamap Australia is an example of this kind of technology (Butler et al., 2017; http://seamapaustralia.org).

to revolutionize the amount of data collected and information provided to scientists and decision makers. This will extend the observations collected on existing sampling platforms, provide new options for building capacity in developing countries, and improve monitoring globally.

Advances in multi-omic sequencing technology and practice have allowed access to the biodiversity of entire communities, including many microbes which resist cultivation in the laboratory. Among these technologies, the targeted sequencing of phylogenetic marker genes and the mass sequencing of a community's entire genomic content (metagenomic) are currently the most feasible targets. Measures of functional and phylogenetic diversity provide unprecedented insight in to how microbial assemblages both respond to and shape ocean dynamics (Buttigieg et al., 2018). Recent realization of the power of the tools of molecular biology to detect minute amounts of an organism's DNA in seawater has led to processing of water samples to detect species (Thomsen et al., 2012) and even populations (Sigsgaard et al., 2016), however monitoring population size and trend from these data is a challenge that may prove difficult to overcome given differences in the rate of DNA loss between species and variable life spans of DNA in different environmental conditions (although see Thomsen et al., 2017). On the other hand, assessing kinship relationships through shared gene sequences has opened up a new method for estimating population size in challenging situations (Hillary et al., 2018).

Developing cost-effective biological sensors which can provide functional biodiversity information and using these on existing multiple observation platforms, will be a key challenge for the next 10 years. Setting goals and evaluating progress will be important to establish priorities and seeking support. The Biology and Ecosystems Panel is being supported through the PEGASuS Future Earth program to provide the scientific basis for such an evaluation.

CONCLUSION

> *"There is nothing a government hates more than to be well-informed; for it makes the process of arriving at decisions much more complicated and difficult." – John Maynard Keynes, The Times (March 11, 1937); Collected Writings, vol. 21, p. 409.*

Development of global ocean observing capacity for the biological EOVs is on the cusp of a step-change. Current capacity to make large numbers of diverse observations; to automate data processing; to integrate diverse data of known provenance in sophisticated, distributed and federated data systems that make data openly available as Findable, Accessible, Interoperable, and Reusable (FAIR) data; to produce openly available data products and visualizations; and to use robust cutting-edge modeling processes to "fill the gaps" in space and time where observations do not exist (e.g., Hill et al., 2017; Jansen et al., 2018), is certain to fundamentally alter the amount and quality of information and knowledge available to scientists and decision makers into the future. However, the coding and statistical skills required by the data scientists, data system software developers, and modelers, and in some cases the skills required by those responsible for the observations in the first place are considerable. It follows that explicit attention to training and capacity building must be a priority for the marine observation community if the activity of observation and resulting data are to have greatest impact at global scale.

There is little doubt that scientists will continue to expand their understanding of what lives in the ocean, where and how it is changing – it is a key driver for scientists' careers. However, whether this expanding information stream will inform policy and management processes is far harder to evaluate (Banks, 2018). An explicit evaluation of how scientific information contributes to national and international policy debate, and the governance mechanisms that could support an increased role, is essential as we move into the UN Decade and beyond. This will require the backing of political leaders, something that most scientists have little power to influence in their day to day jobs. A concerted effort by industry and scientists to work together with economists and other social scientists, a willingness by managers and policy makers to engage more fully in the scientific process, are needed to improve flows of relevant and timely, quality assured information and stimulate the integration of scientific information into the decision-making process. Coordination and collaboration between marine scientists to share their data openly and promptly thus providing consistent evidence-based messages is one of the few ways that scientists can raise the profile of scientific advice to our political leaders. But if we can achieve this, indicators or summary indicators that are used in decision making will become increasingly data-based and progressive, rather than yet one more review of previously reported information.

Recognizing these broader needs if we are to increase our effectiveness as marine scientists is one of the first steps toward achieving greater impact. As we move into the UN Decade we all need to make an additional effort to collaborate, coordinate and facilitate. In many cases it will require a cultural change in how we collect and share data, a change which the UN Decade is ideally situated to deliver. Members of the GOOS Biology and Ecosystems Panel are one of several groups working together to achieve greater output and impact from our ocean measurements, and we hope that you will join us.

AUTHOR CONTRIBUTIONS

NB, PM, and FM-K developed and wrote the manuscript. VA, SB, LB-C, PB, SC, DC, JD, DD, CJ, RK, DO, L-MR, Y-JS, SS, WA, and PT wrote the specific sections and reviewed the entire manuscript.

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REFERENCES

Abrahms, B., Scales, K. L., Hazen, E. L., Bograd, S. J., Schick, R. S., Robinson, P. W., et al. (2018). Mesoscale activity facilitates energy gain in a top predator. *Proc. R. Soc. B Biol. Sci.* 285:20181101. doi: 10.1098/rspb.2018.1101

Banks, G. (2018). *Whatever Happened to 'Evidence Based Policy Making'? Alf Rattigan Lecture November 20, 2018*. Canberra: Australia New Zealand School of Government.

Bar-On, Y. M., Phillips, R., and Milo, R. (2018). The biomass distribution on Earth. *Proc. Natl. Acad. Sci. U.S.A.* 115, 6506–6511. doi: 10.1073/pnas.1711842115

Battaile, B. C., and Trites, A. W. (2013). Linking reproduction and survival can improve model estimates of vital rates derived from limited time-series counts of pinnipeds and other species. *PLoS One* 8:e7738. doi: 10.1371/journal.pone.0077389

Batten, S. D., Abu-Alhaija, R., Chiba, S., Edwards, M., Graham, G., Jyothibabu, R., et al. (2019). A global plankton diversity monitoring program. *Front. Mar. Sci.* 6:321. doi: 10.3389/fmars.2019.00321

Bax, N. J., Appeltans, W., Brainard, R., Duffy, J. E., Dunstan, P., Hanich, Q., et al. (2018). Linking capacity development to GOOS monitoring networks to achieve sustained ocean observation. *Front. Mar. Sci.* 5:346. doi: 10.3389/fmars.2018.00346

Benson, A., Brooks, C. M., Canonico, G., Duffy, E., Muller-Karger, F., Sosik, H. M., et al. (2018). Integrated observations and informatics improve understanding of changing marine ecosystems. *Front. Mar. Sci.* 5:428. doi: 10.3389/fmars.2018.00428

Beyer, H. L., Kennedy, E. V., Beger, M., Chen, C. A., Cinner, J. E., Darling, E. S., et al. (2018). Risk-sensitive planning for conserving coral reefs under rapid climate change. *Conserv. Lett.* 11:e12587. doi: 10.1111/conl.12587

Biller, S. J., Berube, P. M., Dooley, K., Williams, M., Satinsky, B. M., Hackl, T., et al. (2018). Marine microbial metagenomes sampled across space and time. *Sci. Data* 5:180176. doi: 10.1038/sdata.2018.176

Block, B. A., Jonsen, I. D., Jorgensen, S. J., Winship, A. J., Shaffer, S. A., Bograd, S. J., et al. (2011). Tracking apex marine predator movements in a dynamic ocean. *Nature* 475, 86–90. doi: 10.1038/nature10082

Boersma, P. D., and Rebstock, G. A. (2014). Climate change increases reproductive failure in *Magellanic penguins*. *PLoS One* 9:e85602. doi: 10.1371/journal.pone.0085602

Borggaard, D. L., Gouveia, D. M., Colligan, M. A., Merrick, R., Swails, K. S., Asaro, M. J., et al. (2017). Managing U.S. Atlantic large whale entanglements: four guiding principles. *Mar. Policy* 84, 202–212. doi: 10.1016/j.marpol.2017.06.027

Boss, E., Waite, A., Muller-Karger, F., Yamazaki, H., Wanninkhof, R., Uitz, J., et al. (2018). Beyond chlorophyll fluorescence: the time is right to expand biological measurements in ocean observing programs. *Limnol. Oceanogr. Bull.* 27, 89–90. doi: 10.1002/lob.10243

Bost, C. A., Cotte, C., Bailleul, F., Cherel, Y., Charrassin, J. B., Guinet, C., et al. (2009). The importance of oceanographic fronts to marine birds and mammals of the southern oceans. *J. Mar. Syst.* 78, 363–376. doi: 10.1016/j.jmarsys.2008.11.022

Bourlat, S. J., Borja, A., Gilbert, J., Taylor, M. I., Davies, N., Weisberg, S. B., et al. (2013). Genomics in marine monitoring: New opportunities for assessing marine health status. *Mar. Pollut. Bull.* 74, 19–31. doi: 10.1016/j.marpolbul.2013.05.042

Briscoe, D. K., Hobday, A. J., Carlisle, A., Scales, K., Eveson, J. P., Arrizabalaga, H., et al. (2017). Ecological bridges and barriers in pelagic ecosystems. *Deep Sea Res. Part II Top. Stud. Oceanogr.* 140, 182–192. doi: 10.1016/j.dsr2.2016.11.004

Brodie, S., Lédée, E. J. I., Heupel, M. R., Babcock, R. C., Campbell, H. A., Gledhill, D. C., et al. (2018). Continental-scale animal tracking reveals functional movement classes across marine taxa. *Sci. Rep.* 8:3717. doi: 10.1038/s41598-018-21988-5

Brown, B. L., Watson, M., Minot, S. S., Rivera, M. C., and Franklin, R. B. (2017). MinION^{TM} nanopore sequencing of environmental metagenomes: a synthetic approach. *GigaScience* 6:gix007. doi: 10.1093/gigascience/gix007

Bruford, M. W., Davies, N., Dulloo, M. E., Faith, D. P., and Walters, M. (2017). "Monitoring Changes in Genetic Diversity," in *The GEO Handbook on Biodiversity Observation Networks*, eds M. Walters and R. Scholes (Cham: Springer).

Bunting, P., Rosenqvist, A., Lucas, R., Rebelo, L.-M., Hilarides, L., Thomas, N., et al. (2018). The Global Mangrove Watch – a new global baseline of mangrove extent. *Remote Sens.* 10:1669. doi: 10.3390/rs10101669

Burke, L., Reytar, K. A., Spalding, M. A., and Perry, A. L. (2011). *Reefs at Risk*. Washington, DC: World Resources Institute, 124.

Butler, C., Lucieer, V., Walsh, P., Flukes, E., and Johnson, C. (2017). *Seamap Australia [Version 1.0] The Development of a National Benthic Marine Classification Scheme for the Australian Continental Shelf. Final Report to the Australian National Data Service (ANDS) High Values Collection #19*. Hobart: Institute for Marine and Antarctic Studies, University of Tasmania.

Buttigieg, P. L., Fadeev, E., Bienhold, C., Hehemann, L., Offre, P., and Boetius, A. (2018). Marine microbes in 4D using time series observation to assess the dynamics of the ocean microbiome and its links to ocean health. *Curr. Opin. Microbiol.* 43, 169–185. doi: 10.1016/j.mib.2018.01.015

Christiansen, F., Dujon, A. M., Sprogis, K. R., Arnould, J. P. Y., and Bejder, L. (2016). Noninvasive unmanned aerial vehicle provides estimates of the energetic cost of reproduction in humpback whales. *Ecosphere* 7:e01468. doi: 10.1002/ecs2.1468

Constable, A. J. (2011). Lessons from CCAMLR on the implementation of the ecosystem approach to managing fisheries. *Fish Fish.* 12, 138–151. doi: 10.1111/j.1467-2979.2011.00410.x

Costa, D. P., Block, B. A., Bograd, S., Fedak, M. A., and Gunn, J. S. (2010). TOPP as a marine life observatory: using electronic tags to monitor the movements, behaviour and habitats of marine vertebrates. *Proc. OceanObs* 9, 21–25.

Costa, D. P., Breed, G. A., and Robinson, P. W. (2012). New Insights into pelagic migrations: implications for ecology and conservation. *Annu. Rev. Ecol. Evol. Syst.* 43, 73–96. doi: 10.1146/annurev-ecolsys-102710-145045

Crespo, G. O., and Dunn, D. C. (2017). A review of the impacts of fisheries on open-ocean ecosystems. *ICES J. Mar. Sci.* 74, 2283–2297. doi: 10.1098/rsbl.2015.0976

Croll, D. A., Marinovic, B., Benson, S., Chavez, F. P., Black, N., Ternullo, R., et al. (2005). From wind to whales: trophic links in a coastal upwelling system. *Mar. Ecol. Progr. Ser.* 289, 117–130. doi: 10.3354/meps289117

Cubaynes, H. C., Fretwell, P. T., Bamford, C., Gerrish, L., and Jackson, J. A. (2018). Whales from space: four mysticete species described using new VHR satellite imagery. *Mar. Mammal Sci.* 35, 466–491. doi: 10.1111/mms.12544

Davies, N., Field, D., Amaral-Zettler, L., Clark, M. S., Deck, J., Drummond, A., et al. (2014). The founding charter of the genomic observatories network. *Gigascience* 3:2. doi: 10.1186/2047-217X-3-2

De Pooter, D., Appeltans, W., Bailly, N., Bristol, S., Deneudt, K., Eliezer, M., et al. (2017). Toward a new data standard for combined marine biological and environmental datasets - expanding OBIS beyond species occurrences. *Biodiver. Data J.* 5:e10989. doi: 10.3897/BDJ.5.e10989

Descamps, S., Tarroux, A., Varpe, O., Yoccoz, N. G., Tveraa, T., and Lorentsen, S. H. (2015). Demographic effects of extreme weather events: snow storms, breeding success, and population growth rate in a long-lived Antarctic seabird. *Ecol. Evol.* 5, 314–325. doi: 10.1002/ece3.1357

Desprez, M., McMahon, C. R., Hindell, M. A., Harcourt, R., and Gimenez, O. (2013). Known unknowns in an imperfect world: incorporating uncertainty in recruitment estimates using multi-event capture-recapture models. *Ecol. Evol.* 3, 4658–4668. doi: 10.1002/ece3.846

Doughty, C. E., Roman, J., Faurby, S., Wolf, A., Haque, A., Bakker, E. S., et al. (2016). Global nutrient transport in a world of giants. *Proc. Natl. Acad. Sci. U.S.A.* 113, 868–873. doi: 10.1073/pnas.1502549112

Dubilier, N., McFall-Ngai, M., and Zhao, L. (2015). Microbiology: create a global microbiome effort. *Nature* 526, 631–634. doi: 10.1038/526631a

Ducklow, H. W., Fraser, W. R., Meredith, M. P., Stammerjohn, S. E., Doney, S. C., and Martinson, D. G. (2013). West Antarctic Peninsula: an ice-dependent coastal marine ecosystem in transition. *Oceanography* 26, 190–203. doi: 10.5670/oceanog.2013.62

Duffy, J. E., Benedetti-Cecchi, L., Trinanes, J. A., Muller-Karger, F. E., Ambo-Rappe, R., and Boström, C. (2019). Toward a coordinated global observing system for seagrasses and marine macroalgae. *Front. Mar. Sci.* 6:317. doi: 10.3389/fmars.2019.00317

Duke, N. C., Kovacs, J. M., Griffiths, A. D., Preece, L., Hill, D. J. E., van Oosterzee, P., et al. (2017). Large-scale dieback of mangroves in Australia's Gulf of Carpentaria: a severe ecosystem response, coincidental with an unusually extreme weather event. *Mar. Freshw. Res.* 68, 1816–1829.

Dunstan, P. K., Bax, N. J., Dambacher, J. M., Hayes, K. R., Hedge, P. T., Smith, D. S., et al. (2016). Using ecologically or biologically significant marine areas (EBSAs) to implement marine spatial planning. *Ocean Coast. Manag.* 121, 116–127. doi: 10.1016/j.ocecoaman.2015.11.021

Dunstan, P. K., Foster, S. D., King, E., Risbey, J., O'Kane, T. J., Monselesan, D., et al. (2018). Global patterns of change and variation in sea surface temperature and chlorophyll a. *Sci. Rep.* 8:14624. doi: 10.1038/s41598-018-33057-y

Edgar, G. J., and Stuart-Smith, R. D. (2014). Systematic global assessment of reef fish communities by the reef life survey program. *Sci. Data* 1:140007. doi: 10.1038/sdata.2014.7

Eriksen, M., Lebreton, L. C., Carson, H. S., Thiel, M., Moore, C. J., Borerro, J. C., et al. (2014). Plastic pollution in the world's oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. *PLoS One* 9:e111913. doi: 10.1371/journal.pone.0111913

Estes, J. A., Heithaus, M., McCauley, D. J., Rasher, D. B., and Worm, B. (2016). Megafaunal impacts on structure and function of ocean ecosystems. *Annu. Rev. Environ. Resour.* 41, 83–116. doi: 10.1146/annurev-environ-110615-085622

Estes, J. A., Morissette, L., Smith, C., Costa, D., and McCarthy, J. (2014). Whales as marine ecosystem engineers. *Front. Ecol. Environ.* 12, 377–385.

FAO (2008). *Loss of Mangroves Alarming*. Rome: Food and Agriculture Organization of the United Nations.

Fretwell, P. T., LaRue, M. A., Morin, P., Kooyman, G. L., Wienecke, B., Ratcliffe, N., et al. (2012). An emperor penguin population estimate: The first global, synoptic survey of a species from space. *PLoS One* 7:e33751. doi: 10.1371/journal.pone.0033751

Fretwell, P. T., Phillips, R. A., Brooke, A., Fleming, H., and McArthur, A. (2015). Using the unique spectral signature of guano to identify unknown seabird colonies. *Remote Sens. Environ.* 156, 448–456. doi: 10.1016/j.rse.2014.10.011

Fretwell, P. T., Scofield, P., and Phillips, R. A. (2017). Using super-high resolution satellite imagery to census threatened albatrosses. *IBIS* 159, 481–490. doi: 10.1111/ibi.12482

Fretwell, P. T., Staniland, I. J., and Forcada, J. (2014). Whales from Space: counting Southern Right Whales by satellite. *PLoS One* 9:e88655. doi: 10.1371/journal.pone.0088655

GBIF (2018). *Global Biodiversity Information Facility*. Available at: https://www.gbif.org (accessed December 18, 2018).

GCRMN (2017). *Value Proposition and Description of the Global Coral Reef Monitoring Network (GCRMN)*. Paris: IOC.

GCRMN (2018). *GCRMN Implementation and Governance Plan*. Monaco: International Coral Reef Initiative (ICRI).

Girard, C., Tucker, A. D., and Calmettes, B. (2009). Post-nesting migrations of loggerhead sea turtles in the Gulf of Mexico: dispersal in highly dynamic conditions. *Mar. Biol.* 156, 1827–1839. doi: 10.1007/s00227-009-1216-z

Goebel, M. E., Perryman, W. L., Hinke, J. T., Krause, D. J., Hann, N. A., Gardner, S., et al. (2015). A small unmanned aerial system for estimating abundance and size of Antarctic predators. *Polar Biol.* 38, 619–630. doi: 10.1007/s00300-014-1625-4

Goetze, J. S., Bond, T., McLean, D. L., Saunders, B. J., Langlois, T. J., Lindfield, S., et al. (2019). A field and video analysis guide for diver operated stereo-video. *Methods Ecol. Evol.* 10, 1083–1090. doi: 10.1111/2041-210X.13189

Goodwin, K. D., Thompson, L. R., Duarte, B., Kahlke, T., Thompson, A. R., Marques, J. C., et al. (2017). DNA sequencing as a tool to monitor marine ecological status. *Front. Mar. Sci.* 4:107. doi: 10.3389/fmars.2017.00107

Grech, A., Chartrand-Miller, K., Erftemeijer, P., Fonseca, M., McKenzie, L., Rasheed, M., et al. (2012). A comparison of threats, vulnerabilities and management approaches in global seagrass bioregions. *Environ. Res. Lett.* 7:024006. doi: 10.1088/1748-9326/7/2/024006

Gutowsky, S. E., Tremblay, Y., Kappes, M. A., Flint, E. N., Klavitter, J., Laniawe, L., et al. (2014). Divergent post-breeding distribution and habitat associations of fledgling and adult Black-footed Albatrosses Phoebastria nigripes in the North Pacific. *Ibis* 156, 60–72. doi: 10.1111/ibi.12119

Harcourt, R., Sequeira, A. M. M., Zhang, X., Roquet, F., Komatsu, K., Heupel, M., et al. (2019). Animal-borne telemetry: an integral component of the ocean observing toolkit. *Front. Mar. Sci.* 6:326.

Harrison, A. L., Costa, D. P., Winship, A. J., Benson, S. R., Bograd, S. J., Antolos, M., et al. (2018). The political biogeography of migratory marine predators. *Nat. Ecol. Evol.* 2, 1571–1578. doi: 10.1038/s41559-018-0646-8

Hatfield, J. S. (2013). Population Dynamics of Hawaiian seabird colonies vulnerable to sea-level rise. *Conserv. Biol.* 27, 238–238. doi: 10.1111/j.1523-1739.2012.01853.x

Hazen, E. L., Jorgensen, S., Rykaczewski, R. R., Bograd, S. J., Foley, D. G., Jonsen, I. D., et al. (2013). Predicted habitat shifts of Pacific top predators in a changing climate. *Nat. Clim. Change* 3, 234–238. doi: 10.1038/nclimate1686

Hildebrand, J. A., Baumann-Pickering, S., Frasier, K. E., Trickey, J. S., Merkens, K. P., Wiggins, S. M., et al. (2015). Passive acoustic monitoring of beaked whale densities in the Gulf of Mexico. *Sci. Rep.* 5:16343. doi: 10.1038/srep16343

Hill, N. A., Barrett, N., Ford, J. H., Peel, D., Foster, S., Lawrence, E., et al. (2018). Developing indicators and a baseline for monitoring demersal fish in data-poor, offshore Marine Parks using probabilistic sampling. *Ecol. Indic.* 89, 610–621. doi: 10.1016/j.ecolind.2018.02.039

Hill, N. A., Foster, S. D., Duhamel, G., Welsford, D., Koubb, I. P., and Johnson, C. R. (2017). Model-based mapping of assemblages for ecology and conservation management: a case study of demersal fish on the Kerguelen Plateau. *Divers. Distrib.* 23, 1216–1230. doi: 10.1111/ddi.12613

Hill, N. A., Lucieer, V., Barrett, N. S., Anderson, T. J., and Williams, S. B. (2014). Filling the gaps: predicting the distribution of temperate reef biota using high resolution biological and acoustic data. *Estuar. Coast. Shelf Sci.* 147, 137–147. doi: 10.1016/j.ecss.2014.05.019

Hillary, R. M., Bravington, M. V., Patterson, T. A., Grewe, P., Bradford, R., Feutry, P., et al. (2018). Genetic relatedness reveals total population size of white sharks in eastern Australia and New Zealand. *Sci. Rep.* 8:2661. doi: 10.1038/s41598-018-20593-w

Hindell, M. A., McMahon, C. R., Bester, M. N., Boehme, L., Costa, D., Fedak, M. A., et al. (2016). Circumpolar habitat use in the southern elephant seal: implications for foraging success and population trajectories. *Ecosphere* 7:e01213. doi: 10.1002/ecs2.1213

Hughes, T. P., Kerry, J. T., Ãlvarez-Noriega, M., Ãlvarez-Romero, J. G., Anderson, K. D., Baird, A. H., et al. (2017). Global warming and recurrent mass bleaching of corals. *Nature* 543:373. doi: 10.1038/nature21707

Hussey, N. E., Kessel, S. T., Aarestrup, K., Cooke, S. J., Cowley, P. D., Fisk, A. T., et al. (2015). Aquatic animal telemetry: a panoramic window into the underwater world. *Science* 348:1255642. doi: 10.1126/science.1255642

Hutchins, D. A., Fu, F., Sedwick, P. N., and Stehr, G. (2017). Microorganisms and ocean global change. *Nat. Microbiol.* 2:17058. doi: 10.1038/nmicrobiol.2017.58

Intergovernmental Panel on Climate Change (2018). *Global Warming of 1.5° C: An IPCC Special Report on the Impacts of Global Warming of 1.5° C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*. Geneva: Intergovernmental Panel on Climate Change.

Jansen, J., Hill, N. A., Dunstan, P. K., McKinlay, J., Sumner, M. D., Post, A. L., et al. (2018). Abundance and richness of key Antarctic seafloor fauna correlates with modelled food-availability. *Nat. Ecol. Evol.* 2, 71–80. doi: 10.1038/s41559-017-0392-3

Jennings, S., and Kaiser, M. J. (1998). The effects of fishing on marine ecosystems. *Adv. Mar. Biol.* 34, 201–352. doi: 10.1016/s0065-2881(08)60212-6

Kallmeyer, J., Pockalny, R., Adhikari, R. R., Smith, D. C., and D'Hondt, S. (2012). Global distribution of microbial abundance and biomass in subseafloor sediment. *Proc. Natl. Acad. Sci. U.S.A.* 109, 16213–16216. doi: 10.1073/pnas.1203849109

Kirkman, S. P., Yemane, D., Oosthuizen, W. H., Meyer, M. A., Kotze, P. G. H., Skrypzeck, H., et al. (2013). Spatio-temporal shifts of the dynamic Cape fur seal population in southern Africa, based on aerial censuses (1972-2009). *Mar. Mammal Sci.* 29, 497–524. doi: 10.1111/j.1748-7692.2012.00584.x

Kopf, A., Bicak, M., Kottmann, R., Schnetzer, J., Kostadinov, I., Lehmann, K., et al. (2015). The ocean sampling day consortium. *Gigascience* 4:27. doi: 10.1186/s13742-015-0066-5

Koslow, J. A., Boehlert, G. W., Gordon, J. D. M., Haedrich, R. L., Lorance, P., and Parin, N. (2000). Continental slope and deep-sea fisheries: implications for a fragile ecosystem. *ICES J. Mar. Sci.* 57, 548–557. doi: 10.1006/jmsc.2000.0722

Krause, D. J., Hinke, J. T., Perryman, W. L., Goebel, M. E., and LeRoi, D. J. (2017). An accurate and adaptable photogrammetric approach for estimating the mass and body condition of pinnipeds using an unmanned aerial system. *PLoS One* 12:20. doi: 10.1371/journal.pone.0187465

Kusel, E. T., Munoz, T., Siderius, M., Mellinger, D. K., and Heimlich, S. (2017). Marine mammal tracks from two-hydrophone acoustic recordings made with a glider. *Ocean Sci.* 13, 273–288. doi: 10.5194/os-13-273-2017

LaRue, M. A., Rotella, J. J., Garrott, R. A., Siniff, D. B., Ainley, D. G., Stauffer, G. E., et al. (2011). Satellite imagery can be used to detect variation in abundance of Weddell seals (*Leptonychotes weddellii*) in Erebus Bay, Antarctica. *Polar Biol.* 34, 1727–1737. doi: 10.1007/s00300-011-1023-0

LaRue, M. A., Stapleton, S., and Anderson, M. (2017). Feasibility of using high-resolution satellite imagery to assess vertebrate wildlife populations. *Conserv. Biol.* 31, 213–220. doi: 10.1111/cobi.12809

Lent, R., and Squires, D. (2017). Reducing marine mammal bycatch in global fisheries: An economics approach. *Deep Sea Res. Part II Top. Stud. Oceanogr.* 140, 268–277. doi: 10.1016/j.dsr2.2017.03.005

Levin, L. A., Bett, B. J., Gates, A. R., Helmbach, P., Howe, B. M., Janssen, F., et al. (2019). Global observing needs in the deep ocean. *Front. Mar. Sci.* 6:241. doi: 10.3389/fmars.2019.00241

Lewison, R., Wallace, B., Alfaro-Shigueto, J., Mangel, J. C., Maxwell, S. M., and Hazen, E. L. (2013). "Fisheries bycatch of marine turtles," in *Lessons Learned From Decades of Research and Conservation Biology of Sea Turtles, Vol III*, eds J. Wyneken, K. J. Lohmann, and J. A. Musick (Boca Raton, FL: CRC Press).

Lindstrom, E., Gunn, J., Fischer, A., McCurdy, L. K., and Glover, A. (2012). *A Framework for Ocean Observing. IOC Information Document - 1284*. Paris: UNESCO.

Lombard, F., Boss, E., Waite, A. M., Vogt, M., Uitz, J., Stemmann, L., et al. (2019). Globally consistent quantitative observations of planktonic ecosystems. *Front. Mar. Sci.* 6:196. doi: 10.3389/fmars.2019.00196

MacIntyre, K. Q., Stafford, K. M., Conn, P. B., Laidre, K. L., and Boveng, P. L. (2015). The relationship between sea ice concentration and the spatio-temporal distribution of vocalizing bearded seals (*Erignathus barbatus*) in the Bering, Chukchi, and Beaufort Seas from 2008 to 2011. *Progr. Oceanogr.* 136, 241–249. doi: 10.1016/j.pocean.2015.05.008

McCauley, D. J., Pinsky, M. L., Palumbi, S. R., Estes, J. A., Joyce, F. H., and Warner, R. R. (2015). Marine defaunation: animal loss in the global ocean. *Science* 347:1255641. doi: 10.1126/science.1255641

McQuillan, J. S., and Robidart, J. C. (2017). Molecular-biological sensing in aquatic environments: recent developments and emerging capabilities. *Curr. Opin. Biotechnol* 45, 43–50. doi: 10.1016/j.copbio.2016.11.022

Miloslavich, P., Bax, N. J., Simmons, S. E., Klein, E., Appeltans, W., Aburto-Oropeza, O., et al. (2018a). Essential ocean variables for global sustained observations of biodiversity and ecosystem changes. *Glob. Change Biol.* 24, 2416–2433. doi: 10.1111/gcb.14108

Miloslavich, P., Seeyave, S., Muller-Karger, F., Bax, N., Ali, E., Delgado, C., et al. (2018b). Challenges for global ocean observation: the need for increased human capacity. *J. Operat. Oceanogr.* 1–20. doi: 10.1080/1755876X.2018.1526463

Miloslavich, P., Pearlman, J., and Kudela, R. (2018c). *Sustainable Observations of Plankton, the Sea's Food Foundation*. Available at: https://eos.org/meeting-reports/sustainable-observations-of-plankton-the-seas-food-foundation (accessed November 11, 2018).

Monk, J., Barrett, N., Bridge, T., Carroll, A., Friedman, A., Jordan, A., et al. (2018). *Marine Sampling Field Manual for AUV's (Autonomous Underwater Vehicles)*. Canberra: NESP Marine Biodiversity Hub.

Moore, J. E., and Barlow, J. P. (2013). Declining abundance of beaked whales (family Ziphiidae) in the California Current large marine ecosystem. *PLoS ONE* 8:e52770. doi: 10.1371/journal.pone.0052770

Moore, J. E., Wallace, B. P., Lewison, R. L., Zydelis, R., Cox, T. M., and Crowder, L. B. (2009). A review of marine mammal, sea turtle and seabird bycatch in USA fisheries and the role of policy in shaping management. *Mar. Policy* 33, 435–451. doi: 10.1016/j.marpol.2008.09.003

Moran, M. A. (2015). The global ocean microbiome. *Science* 80:8455. doi: 10.1126/science.aac8455

Moss, B. (2017). Marine reptiles, birds and mammals and nutrient transfers among the seas and the land: an appraisal of current knowledge. *J. Exp. Mar. Biol. Ecol.* 492, 63–80. doi: 10.1016/j.jembe.2017.01.018

Muller-Karger, F. E., Kavanaugh, M. Y., Montes, E., Balch, W. M., Breitbart, M., Chavez, F. P., et al. (2014). A framework for a marine biodiversity observing network within changing continental shelf seascapes. *Oceanography* 27, 18–23. doi: 10.5670/oceanog.2014.56

Muller-Karger, F. E., Hestir, E., Ade, C., Turpie, K., Roberts Dar, A., Siegel, D., et al. (2018a). Satellite sensor requirements for monitoring essential biodiversity variables of coastal ecosystems. *Ecol. Appl.* 28, 749–760. doi: 10.1002/eap.1682

Muller-Karger, F. E., Miloslavich, P., Bax, N. J., Simmons, S., Costello, M. J., Sousa Pinto, I., et al. (2018b). Advancing marine biological observations and data requirements of the complementary essential Ocean variables (EOVs) and essential biodiversity variables (EBVs) frameworks. *Front. Mar. Sci.* 5:211. doi: 10.3389/fmars.2018.00211

Munger, L., Lammers, M. O., Cifuentes, M., Würsig, B., Jefferson, T. A., and Hung, S. K. (2016). Indo-Pacific humpback dolphin occurrence north of Lantau Island, Hong Kong, based on year-round passive acoustic monitoring. *J. Acoust. Soc. Am.* 140, 2754–2765. doi: 10.1121/1.4963874

Nordlund, L. M., Koch, E. W., Barbier, E. B., and Creed, J. C. (2016). Seagrass ecosystem services and their variability across genera and geographical regions. *PLoS One* 11:e0163091. doi: 10.1371/journal.pone.0163091

Pardo, D., Jenouvrier, S., Weimerskirch, H., and Barbraud, C. (2017). Effect of extreme sea surface temperature events on the demography of an age-structured albatross population. *Philos. Trans. R. Soc. B-Biol. Sci.* 372:20160143. doi: 10.1098/rstb.2016.0143

Patricio, J., Little, S., Mazik, K., Papadopoulou, K.-N., Smith, C. J., Teixeira, H., et al. (2016). European marine biodiversity monitoring networks: strengths, weaknesses, opportunities and threats. *Front. Mar. Sci.* 3:161.

Pauly, D., Hilborn, R., and Branch, T. A. (2013). Fisheries: does catch reflect abundance? *Nature* 494, 303–306. doi: 10.1038/494303a

Peckham, S. H., Maldonado-Diaz, D., Tremblay, Y., Ochoa, R., Polovina, J., and Balazs, G. (2011). Demographic implications of alternative foraging strategies in juvenile loggerhead turtles Caretta caretta of the North Pacific Ocean. *Mar. Ecol. Progr. Ser.* 425, 269–280. doi: 10.3354/meps08995

Pereira, H. M., Ferrier, S., Walters, M., Geller, G. N., Jongman, R. H. G., Scholes, R. J., et al. (2013). Essential biodiversity variables. *Science* 339, 277–278.

Pesant, S., Grigorov, I., Malfatti, F., Magalhães, C., Vezzi, A., Poulain, J., et al. (2017). *EMOSE (2017) Inter-Comparison of Marine Plankton Metagenomic Analysis Methods*. Charlottesville, VA: OSF.

Poloczanska, E. S., Brown, C. J., Sydeman, W. J., Kiessling, W., Schoeman, D. S., Moore, P. J., et al. (2013). Global imprint of climate change on marine life. *Nat. Clim. Chang.* 3, 919–925. doi: 10.1038/nclimate1958

Proud, R., Handegard, N. O., Kloser, R., Cox, M., and Brierley, A. S. (2018). From siphonophores to deep scattering layers: uncertainty ranges for the estimation of global mesopelagic fish biomass. *ICES J. Mar. Sci.* 76, 718–733. doi: 10.1093/icesjms/fsy037

Prowe, A. F., Pahlow, M., Dutkiewicz, S., Follows, M., and Oschlies, A. (2012). Topdown control of marine phytoplankton diversity in a global ecosystem model. *Progr. Oceanogr.* 101, 1–13. doi: 10.1016/j.pocean.2011.11.016

Przeslawski, R., Foster, F., Monk, J., Barrett, N., Bouchet, P., Carroll, A. G., et al. (2019). A suite of field manuals for marine sampling to monitor Australian waters. *Front. Mar. Sci.* 6:177. doi: 10.3389/fmars.2019.00177

Reid, K., Croxall, J., Briggs, D. R., and Murphy, E. J. (2005). Antarctic ecosystem monitoring: quantifying the response of ecosystem indicators to variability in Antarctic krill. *ICES J. Mar. Sci.* 62, 366–373. doi: 10.1016/j.icesjms.2004.11.003

Rhein, M., Rintoul, S. R., Aoki, S., Campos, E., Chambers, D., Feely, R. A., et al. (2013). *Observations: Ocean in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

Roelfsema, C., Kovacs, E., Roos, P., Terzano, D., Lyons, M., and Phinn, S. (2018). Use of a semi-automated object based analysis to map benthic composition, Heron Reef, Southern Great Barrier Reef. *Remote Sens. Lett.* 9, 324–333. doi: 10.1080/2150704x.2017.1420927

Roman, J., Estes, J. A., Morissette, L., Smith, C., Costa, D., McCarthy, J., et al. (2014). Whales as marine ecosystem engineers. *Front. Ecol. Environ.* 12, 377–385.

Romanach, S. S., DeAngelis, D. L., Koh, H. L., Li, Y., Teh, S. Y., Raja Barizan, R. S., et al. (2018). Conservation and restoration of mangroves: global status, perspectives, and prognosis. *Ocean Coast. Manag.* 154, 72–82. doi: 10.1016/j.ocecoaman.2018.01.009

Roquet, F., Williams, G., Hindell, M. A., Harcourt, R., McMahon, C., Guinet, C., et al. (2014). A Southern Indian Ocean database of hydrographic profiles obtained with instrumented elephant seals. *Sci. Data* 1:140028. doi: 10.1038/sdata.2014.28

Rotella, J. J., Link, W. A., Chambert, T., Stauffer, G. E., and Garrott, R. A. (2012). Evaluating the demographic buffering hypothesis with vital rates estimated for Weddell seals from 30 years of mark-recapture data. *J. Anim. Ecol.* 81, 162–173. doi: 10.1111/j.1365-2656.2011.01902.x

Rusch, D. B., Halpern, A. L., Sutton, G., Heidelberg, K. B., Williamson, S., Yooseph, S., et al. (2007). The Sorcerer II Global Ocean Sampling expedition: northwest Atlantic through eastern tropical Pacific. *PLoS Biol.* 5:e77.

Schmidtko, S., Stramma, L., and Visbeck, M. (2017). Decline in global oceanic oxygen content during the past five decades. *Nature* 542, 335–339. doi: 10.1038/nature21399

Scholin, C., Birch, J., Jensen, S., Marin, R., Massion, E., Pargett, D., et al. (2017). The quest to develop ecogenomic sensors: A 25-year history of the environmental sample processor (ESP) as a case study. *Oceanography* 30, 100–113. doi: 10.5670/oceanog.2017.427

Sczyrba, A., Hofmann, P., Belmann, P., Koslicki, D., Janssen, S., Dröge, J., et al. (2017). Critical assessment of metagenome interpretation—a benchmark of metagenomics software. *Nat. Methods* 14:1063. doi: 10.1038/nmeth.4458

Sequeira, A. M. M., Rodríguez, J. P., Eguíluz, V. M., Harcourt, R., Hindell, M., Sims, D. W., et al. (2018). Convergence of marine megafauna movement patterns in coastal and open oceans. *Proc. Natl. Acad. Sci. U.S.A.* 115, 3072–3077. doi: 10.1073/pnas.1716137115

Shin, Y.-J., Bundy, A., Shannon, L. J., Blanchard, J., Chuenpagdee, R., Knight, B., et al. (2012). Global in scope and regionally rich: an IndiSeas workshop helps shape the future of marine ecosystem indicators. *Rev. Fish Biol. Fish.* 22, 835–845. doi: 10.1007/s11160-012-9252-z

Sigsgaard, E. E., Nielsen, I. B., Bach, S. S., Lorenzen, E. D., Robinson, D. P., and Knudsen, S. W. (2016). Population characteristics of a large whale shark aggregation inferred from seawater environmental DNA. *Nat. Ecol. Evol.* 1:4. doi: 10.1038/s41559-016-0004

Širovic, A., Rice, A., Chou, E., Hildebrand, J. A., Wiggins, S. M., and Roch, M. A. (2015). Seven years of blue and fin whale call abundance in the Southern California Bight. *Endanger. Spec. Res.* 28, 61–76. doi: 10.3354/esr00676

Southwell, C., Bengtson, J., Bester, M., Blix, A. S., Bornemann, H., Boveng, P., et al. (2012). A review of data on abundance, trends in abundance, habitat use and diet of ice-breeding seals in the Southern Ocean. *CCAMLR Sci.* 19, 49–74.

Southwell, C., Emmerson, L., Takahashi, A., Barbraud, C., Delord, K., and Weimerskirch, H. (2017). Large-scale population assessment informs conservation management for seabirds in Antarctica and the Southern Ocean: a case study of *Adelie penguins*. *Glob. Ecol. Conserv.* 9, 104–115. doi: 10.1016/j.gecco.2016.12.004

Stall, S., Yarmey, L., Cutcher-Gershenfeld, J., Hanson, B., Lernhert, K., Nosek, B., et al. (2019). Make scientific data FAIR'. *Nature* 570, 27–29. doi: 10.1038/d41586-019-01720-7

Stock, C. A., John, J. G., Rykaczewski, R. R., Asch, R. G., Cheung, W. W. L., Dunne, J. P., et al. (2017). Reconciling fisheries catch and ocean productivity. *Proc. Natl. Acad. Sci.U.S.A.* 114, E1441–E1449. doi: 10.1073/pnas.1610238114

Sunagawa, S., Coelho, L. P., Chaffron, S., Kultima, J. R., Labadie, K., Salazar, G., et al. (2015). Structure and function of the global ocean microbiome. *Science* 348, 1261359–1261359. doi: 10.1126/science.1261359

Suryan, R. M., Anderson, D. J., Shaffer, S. A., Roby, D. D., Tremblay, Y., Costa, D. P., et al. (2008). Wind, waves, and wing loading: morphological specialization may limit range expansion of endangered albatrosses. *PLoS One* 3:e4016. doi: 10.1371/journal.pone.0004016

Tew Kai, E., Rossi, V., Sudre, J., Weimerskirch, H., Lopez, C., Hernandez-Garcia, E., et al. (2009). Top marine predators track Lagrangian coherent structures. *Proc. Natl. Acad. Sci. U.S.A.* 106, 8245–8250. doi: 10.1073/pnas.0811034106

Thompson, L. R., Sanders, J. G., McDonald, D., Amir, A., Ladau, J., Locey, K. J., et al. (2017). A communal catalogue reveals earth's multiscale microbial diversity. *Nature* 551, 457–463. doi: 10.1038/nature24621

Thomsen, P. F., Kielgast, J., Iversen, L. L., Moller, P. R., Rasmussen, M., and Willerslev, E. (2012). Detection of a diverse marine fish fauna using environmental DNA from seawater samples. *PLoS One* 7:e41732. doi: 10.1371/journal.pone.0041732

Thomsen, P. F., Moller, P. R., Sigsgaard, E. E., Knudsen, S. W., Jorgensen, O. A., and Willerslev, E. (2017). Environmental DNA from seawater samples correlate with trawl catches of Subarctic. Deepwater Fishes. *PLoS One* 11:e0165252. doi: 10.1371/journal.pone.0165252

Thorne, L. H., Conners, M. G., Hazen, E. L., Bograd, S. J., Antolos, M., Costa, D. P., et al. (2016). Effects of El Nino-driven changes in wind patterns on North Pacific albatrosses. *J. R. Soc. Interface* 13:20160196. doi: 10.1098/rsif.2016.0196

Thresher, R. E., Tilbrook, B., Fallon, S. J., Wilson, N. C., and Adkins, J. (2011). Effects of chronic low carbonate saturation levels on the distribution, growth and skeletal chemistry of deep-sea corals and other seamount megabenthos. *Mar. Ecol. Prog. Ser.* 442, 87–99. doi: 10.3354/meps09400

Tompkins, E. M., Townsend, H. M., and Anderson, D. J. (2017). Decadal-scale variation in diet forecasts persistently poor breeding under ocean warming in a tropical seabird. *PLoS One* 12:e0182545. doi: 10.1371/journal.pone.0182545

Trathan, P. N., Fretwell, P. T., and Stonehouse, B. (2011). First Recorded Loss of an Emperor Penguin Colony in the Recent Period of Antarctic Regional Warming: Implications for Other Colonies. *PLoS One* 6:e14738. doi: 10.1371/journal.pone.0014738

Treasure, A. M., Roquet, F., Ansorge, I. J., Bester, M. N., Boehme, L., Bornemann, H., et al. (2017). Marine mammals exploring the oceans pole to pole a review of the MEOP consortium. *Oceanography* 30, 132–138. doi: 10.5670/oceanog.2017.234

Tynan, C. T. (1998). Ecological importance of the Southern Boundary of the Antarctic Circumpolar Current. *Nature* 392, 708–710. doi: 10.1002/ece3.2833

Unsworth, R., Nordlund, L. M., and Cullen-Unsworth, L. C. (2018). Seagrass meadows support global fisheries production. *Conserv. Lett.* 8:e12566. doi: 10.1111/conl.12566

van Hooidonk, R., Maynard, J., Tamelander, J., Gove, J., Ahmadia, G., Raymundo, L., et al. (2016). Local-scale projections of coral reef futures and implications of the Paris Agreement. *Sci. Rep.* 6:39666. doi: 10.1038/srep39666

Wallace, B. P., DiMatteo, A. D., Bolten, A. B., Chaloupka, M. Y., Hutchinson, B. J., Abreu-Grobois, F. A., et al. (2011). Global conservation priorities for marine turtles. *PLoS One* 6:e24510. doi: 10.1371/journal.pone.0024510

Watson, R. A., Pitcher, T. J., and Jennings, S. (2017). Plenty more fish in the sea? *Fish Fish.* 18, 105–113. doi: 10.1111/faf.12128

Waycott, M., Duarte, C. M., Carruthers, T. J., Orth, R. J., Dennison, W. C., Olyarnik, S., et al. (2009). Accelerating loss of seagrasses across the globe threatens coastal ecosystems. *Proc. Natl. Acad. Sci. U.S.A.* 106, 12377–12381. doi: 10.1073/pnas.0905620106

Weimerskirch, H., Bouard, F., Ryan, P. G., and Bost, C. A. (2018). Massive decline of the world's largest king penguin colony at Ile aux

Cochons, Crozet. *Antarct. Sci.* 30, 236–242. doi: 10.1017/s0954102018000226

Weimerskirch, H., Guionnet, T., Martin, J., Shaffer, S. A., and Costa, D. (2000). Fast and fuel efficient? Optimal use of wind by flying albatrosses. *Proc. R. Soc. Lond. B Biol. Sci.* 267, 1869–1874. doi: 10.1098/rspb.2000.1223

Weimerskirch, H., Louzao, M., de Grissac, S., and Delord, K. (2012). Changes in wind pattern alter albatross distribution and life-history traits. *Science* 335, 211–214. doi: 10.1126/science.1210270

Wilkinson, C. (ed.) (2000). *Status of Coral Reefs of the World: 2000*. Townsville: Australian Institute of Marine Science.

Wilkinson, C. (ed.) (2008). *Status of Coral Reefs of the World: 2008*. Townsville: Australian Institute of Marine Science.

Williams, A., Schlacher, T. A., Rowden, A. A., Althaus, F., Clark, M. R., Bowden, D. A., et al. (2010). Seamount megabenthic assemblages fail to recover from trawling impacts. *Mar. Ecol.* 31, 183–199. doi: 10.1111/j.1439-0485.2010.00385.x

World Meteorological Organization [WMO] (2016). *The Global Observing System for Climate: Implementation Needs*. Geneva: World Meteorological Organization.

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REVIEW
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The European Marine Observation and Data Network (EMODnet): Visions and Roles of the Gateway to Marine Data in Europe

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Marine data are needed for many purposes: for acquiring a better scientific understanding of the marine environment, but also, increasingly, as marine knowledge for decision making as well as developing products and services supporting economic growth. Data must be of sufficient quality to meet the specific users' needs. It must also be accessible in a timely manner. And yet, despite being critical, this timely access to known-quality data proves challenging. Europe's marine data have traditionally been collected by a myriad of entities with the result that much of our data are scattered throughout unconnected databases and repositories. Even when data are available, they are often not compatible, making the sharing of the information and data aggregation particularly challenging. In this paper, we present how the European Marine Observation and Data network (EMODnet) has developed over the last decade to tackle these issues. Today, EMODnet is comprised of more than 150 organizations which gather marine data, metadata, and data products and make them more easily accessible for a wider range of users. EMODnet currently consists of seven sub-portals: bathymetry, geology, physics, chemistry, biology, seabed habitats, and human activities. In addition, Sea-basin Checkpoints have been established to assess the observation capacity in the North Sea, Mediterranean, Atlantic, Baltic, Artic, and Black Sea. The Checkpoints identify whether the observation infrastructure in Europe meets the needs of users by undertaking a number of challenges. To complement this, a Data Ingestion Service has been set up to tackle the problem of the wealth of marine data that remain unavailable, by reaching out to data holders, explaining the benefits of sharing their data and offering a support service to assist them in releasing their data and making them available through EMODnet. The EMODnet Central Portal (www.emodnet.eu) provides a single point of access to these services, which are free to access and use. The strategic vision of EMODnet in the next decade is also presented, together with key focal areas toward a more user-oriented service, including EMODnet for business, internationalization for global users, and stakeholder engagement to connect the diverse communities across the marine knowledge value chain.

Keywords: EMODnet, data portal, open access, checkpoint, data services, marine knowledge, blue economy, data integrator

INTRODUCTION

Access to reliable and accurate ocean data and information is vital for addressing threats to the marine environment, for developing policies and legislation to monitor and protect vulnerable areas of our coasts and oceans, and in understanding trends and forecasting future changes. As highlighted in numerous reports and strategic documents produced by the European Commission (European Commission, 2010, 2012; EEA, 2015) better quality and more easily accessible marine data is a prerequisite for further sustainable economic development, or "blue growth". The potential of Europe's wealth of marine observations to support this growth is huge.

In this paper we will explain how the European Marine Observation and Data network (EMODnet) has evolved over the last decade improving access to marine data, metadata, and data products for a wider range of users. Shepherd (2018) explained the rationale behind the initiative, and its benefits for the blue economy. We will build on this and on Calewaert et al. (2016) (who first introduced EMODnet and highlighted some of its main features, including its thematic data portals) and will further present the remarkable progress achieved in the last years. We will first highlight the most recent developments of the thematic data portals, with a particular focus on three of them, -Physics, Chemistry, and Biology- to illustrate the concepts and multi-disciplinary nature of EMODnet. Furthermore, we will provide insights into how the other EMODnet strands (the Data Ingestion Service, the Sea-basin Checkpoints and the Central Portal) have greatly strengthened the service for users. The paper will also present the vision for EMODnet into the next decade, with renewed efforts toward engaging stakeholders to build a more user-oriented service with global relevance.

Abbreviations: API, Application Programme Interface; ASCII, American Standard Code for Information Interchange; BODC, British Oceanographic Data Centre; CDI, Common Data Index; CF, Climate and Forecast; CMEMS, Copernicus Marine Environment Monitoring Service; CPUE, Catch per Unit Effort; DATRAS, Database of Trawl Surveys; DBCP, Data Buoy Cooperation Panel; DCF, Data Collection Framework; DG GROW, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs; DG MARE, Directorate-General for Maritime Affairs and Fisheries; DG RTD, Directorate-General for Research and Innovation; DIS, Dissolved Inorganic Nitrogen; DIVA, Data-Interpolating Variational Analysis; DOI, Digital Object Identifier; DTM, Digital Terrain Model; DwC, Darwin Core; EAS, European Atlas of the Seas; EC, European Commission; EEA, European Environment Agency; EGDI, European Geological Data Infrastructure; EGO, European Gliding Observatory; EMODnet, European Marine Observation and Data Network; EOV, Essential Ocean Variable; EU, European Union; EurOBIS, European Ocean Biogeographic Information System; GDAC, Global Assembly Data Centre; GEOSS, Global Earth Observation System of Systems; GES, Good Environmental Status; GLOSS, Global Sea Level Observing System; GMES, Global Monitoring for Environment and Security; GOOS, Global Ocean Observing System; GO-SHIP, Global Ocean Ship-based Hydrographic Investigation Programme; GPS, Global Positioning System; GROOM, Gliders for Research Ocean Observation and Management; HELCOM, Helsinki Commission; HF, High Frequency; HFR, High Frequency Radar; ICES, International Council for the Exploration of the Seas; IOG, Intergovernmental Oceanographic Commission; IODE, International Ocean and Data Exchange; IPT, Integrated Publishing Toolkit; ISO, International Standards Organization; JCOMMOPS, Joint Technical Commission of Oceanography and Marine Meteorology *in situ* Observing Platform Support Centre; JERICO, Joint European Research Infrastructure of Coastal Observatories; JRC, Joint Research Centre; JSON, JavaScript Object Notation; M2M, Machine to Machines; MAP, Mediterranean Action Plan; MCS, Marine Conservation Society; MEDITS, Mediterranean International Trawl Survey; MPA, Marine Protected Area; MSc, Master of Science; MSFD, Marine Strategy Framework Directive; MSP, Maritime Spatial Planning; NERC, Natural Environment Research Council; NetCDF, Network Common Data Format; NGO, Non-Governmental Organization; NODC, National Oceanographic Data Centre; NOAA, National Oceanic and Atmospheric Administration; NRT, Near Real Time; OBIS, Ocean Biogeographic Information System; ODV, Ocean Data View; OECD, Organization for Economic Co-operation and Development; OGC, Open Geospatial Consortium; OSPAR, Oslo-Paris (Convention); PhD, Philosophiae Doctor; PSMSL, Permanent Service for Mean Sea Level; QA, Quality Assurance; QC, Quality Control; REST, Representational State Transfer; ROOS, Regional Ocean Observing System; RTD, Research, Technology and Development; SMEs, Small and Medium Enterprises; SOAP, Simple Object Access Protocol; SOOS, Southern Ocean Observing System; SONEL, Systéme d'Observation du Niveau des Eaux Littorales; SWE, Sensor Web Enablement; TAC, Thematic Assembly Centre; THREDDS, Thematic Real-time Environmental Distributed Data; UNEP, United Nations Environment Programme; UNESCO, United Nations Educational, Scientific and Cultural Organization; WCS, Web Coverage Service; WFS, Web Feature Service; WMO, World Meteorological Organization; WMS, Web Map Service; WoRMS, World Register of Marine Species; WPS, Web Processing Service; XML, Exchange Markup Language.

THE CHALLENGE

Ocean and marine data collection in Europe is carried out by hundreds of organizations in many different countries, working across a range of disciplines, and using heterogeneous observing methods and sensors installed on board research vessels, underwater vehicles, fixed and drifting platforms, aircrafts, and satellites. Most data collection, by both private and public organizations, is carried out for a single, specific purpose, often in isolation from each other. Marine data can be generated as a result of marine environmental monitoring obligations, through the activities of maritime and offshore industries and by the research community. Increasingly data are also being generated by citizen science activities. All of these data may have numerous applications beyond the purpose for which they were taken. To anticipate this potential, great progress has already been made, with the development of standards, services, and infrastructures for providing long term storage and means of discovery and access to these valuable data resources. Activities have been undertaken as part of international initiatives, such as the International Ocean and Data Exchange (IODE) program of the Intergovernmental Oceanographic Commission (IOC) of UNESCO or the Working Group on Marine Data Management of the International Council for the Exploration of the Sea (ICES). In Europe, a series of projects have been dedicated to developing the pan-European SeaDataNet[1] infrastructure, and the developments of the EurOBIS[2] (marine biodiversity) and PANGAEA[3] (marine earth science) data portals. However, for a variety of reasons, a large part of these data remained out of reach and thus inaccessible to other potential users, and European-scale cooperation between these data management initiatives was limited. This changed considerably with the launch of EMODnet in 2009, which aimed to establish an overarching European marine data and observation network. The establishment of EMODnet fostered coordination at European Union (EU) level between a number of EU directives and policies (Marine Strategy Framework Directive, Integrated Maritime Policy, Blue Growth) and large-scale observation and data collection framework programs, such as the Global Monitoring for Environment and Security (GMES, now COPERNICUS[4]) and the Global Earth Observation System of Systems (GEOSS[5]).

This is very much in line with one of the major challenges already identified in OceanObs09: the need for improved international and national organizational structures to build and sustain a truly interdisciplinary, coherent, systematic, sustained ocean observing system (Fischer et al., 2010). As we shall see, EMODnet is actively contributing to that endeavor.

THE SOLUTION

EMODnet is the key implementing mechanism of the European Commission's Marine Knowledge 2020 strategy (European Commission, 2010, 2012) to unlock the potential of Europe's wealth of marine data. Based on the principle of collecting data once and using it many times for many purposes, EMODnet is a network of organizations (currently more than 150) supported by the EU's Integrated Maritime Policy[6] linked by a data management structure. These organizations work together to aggregate and process marine data from diverse sources and generate data products. EMODnet provides a gateway to those marine data accompanied by their metadata and data products through a number of thematic portals and a central portal[7]. As Shepherd (2018) outlines, EMODnet's objectives are to:

- Increase productivity in all tasks involving marine data by avoiding re-collection of data and saving costs involved in putting together marine data;
- Increase competition and innovation in established and emerging maritime sectors;
- Reduce uncertainty in our knowledge of the oceans and the seas and improve our ability to forecast the behavior of the seas.

EMODnet DEVELOPMENT

EMODnet's development is based on the following core principles that continue to guide and underpin the strategic expansion of its services:

- Collect data once and use them many times;
- Develop data standards across disciplines as well as within them;
- Process and validate data at different scales: regional, basin and pan-European;
- Build on existing efforts where data communities have already organized themselves;
- Put the user first when developing priorities and taking decisions;
- Provide statements on data ownership, accuracy, and precision;
- Sustainable funding at a European level to maximize benefit from the efforts of individual Member States;
- Free and unrestricted access to data and data products.

These core principles underpinning the development and operation of EMODnet are in alignment with the 2016 FAIR (Findable, Accessible, Interoperable, Re-usable) guiding principles for scientific data management and stewardship (Wilkinson et al., 2016).

Established in 2009, EMODnet is a long-term initiative that has been built through a phased approach (**Table 1**). During the first phase, six prototype data portals were developed. Largely building on existing data repositories, infrastructures, initiatives and projects by specific and distinct communities of experts, these covered a limited selection of sea-basins and parameters, and offered data-products at low resolution.

The second phase saw the data portals expanded to provide full coverage of all European sea-basins. A wider selection of parameters and medium resolution data products were also made

[1] https://www.seadatanet.org/
[2] http://www.eurobis.org/
[3] www.pangaea.de
[4] www.copernicus.eu
[5] https://www.earthobservations.org/geoss.php

[6] The Integrated Maritime Policy has the objective to better coordinate Europe's maritime activities and the management of its marine environment https://ec.europa.eu/maritimeaffairs/policy_en
[7] www.emodnet.eu

TABLE 1 | The three initial phases of EMODnet development up to 2020.

2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Phase I–59 institutions, budget 6.5M Euros • Prototype of thematic data portals • Limited selection of parameters and sea-basins • Low-resolution data products											
				Phase II–120 institutions, budget 16.3M Euros • More parameters, and coverage (all sea-basins) • Medium-resolution data products • Human Activities portal, establishment of Central Portal, Sea-basin Checkpoints, and Secretariat							
								Phase III–More than 150 institutions, budget 20M Euros • Multi-resolution digital map of entire European seabed by 2020			

available. The second phase also included the addition of a new portal on Human Activities and the creation of the cross-cutting EMODnet Central Portal, as well as the establishment of the six regional Sea-basin Checkpoints and the Data Ingestion facility. To oversee and coordinate these growing and diverse activities, an EMODnet Secretariat was also established.

Currently in its third development phase, EMODnet has reached a mature and operational stage where efforts are now focused on maximizing its use and achieving the goal of providing free access to a multi-resolution digital map of the entire European seabed by 2020.

Throughout the different phases, the number of institutions working together within EMODnet has grown from 59 in the first phase to currently more than 150. The budget has also increased with time, having tripled from 6.5M Euros in the early years to 20M Euros in the current phase.

The development of EMODnet has not taken place in isolation. On the contrary, EMODnet has been built on and evolved in close connection with existing initiatives and infrastructures that are also part of the European and global marine data landscape, in particular, SeaDataNet and Copernicus Marine Service (CMEMS) (see **Figure 1**), which will be described briefly below.

After completion of the development phases, EMODnet will continue to develop beyond 2020 as a fully operational user-focused data service for society providing open and free access to marine data and data products that are interoperable with other key European and global data services (see section "EMODnet in the Next Decade").

EMODnet THEMATIC GROUPS

There are seven EMODnet thematic groups, which provide the data management infrastructure of EMODnet: Bathymetry, Geology, Seabed Habitats, Physics, Chemistry, Biology, and Human Activities (see **Table 2** for description of the thematic coverage provided by the portals[8]).

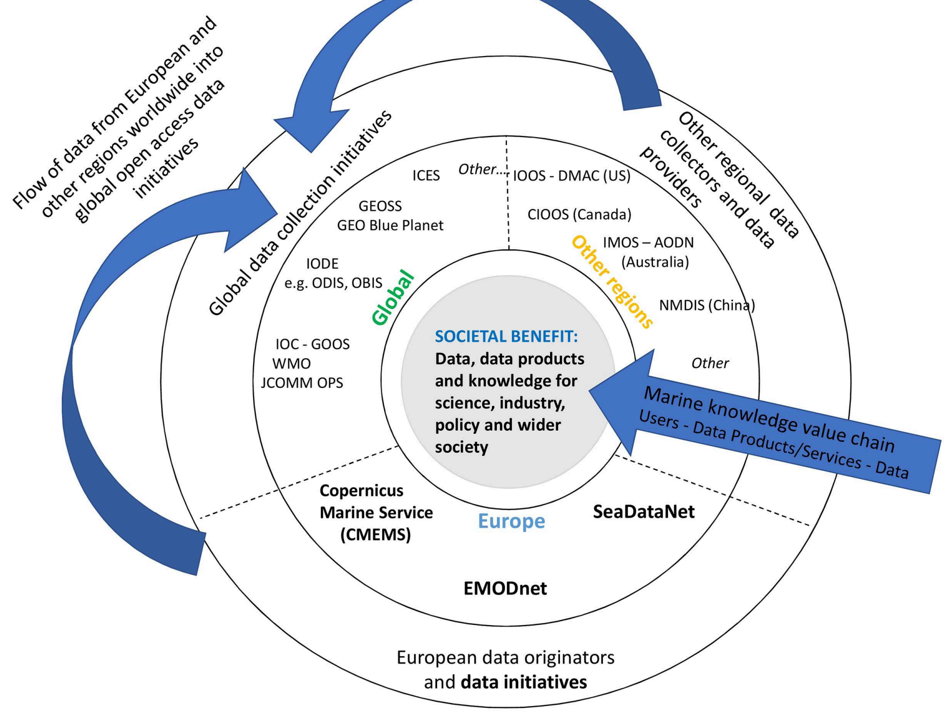
Although quite distinct in nature, each thematic group is underpinned by various data initiatives (data infrastructures, networks, projects, data assembly centers…) which, in turn, receive data from different data originators. EMODnet thematic groups build on those data initiatives and add value by (1) facilitating access to the data and (2) generating new products from them. EMODnet also provides friendly, user-oriented interfaces and services to guarantee an effective access to those data and data products.

Table 3 lists the main data initiatives, together with the ultimate data originators. For instance, the main pillar of the Geology thematic group is the European Geological Data Infrastructure (EGDI[9]), while data originators are mostly geological surveys from across Europe. For Human Activities, data originators are very heterogeneous, both public (port authorities, ministries, European agencies…) and private (industrial clusters). Human Activities assembles data directly from them and not via any intermediary.

More differences are found in the data flow from the data originators to the provision of the data to the users amongst the different EMODnet thematic portals. This data flow comprises several steps including assembling, quality control (QC) and quality assurance (QA) (e.g., metadata curation, data standards compliance checks, control of geographic location, accuracy assessment) as well as harmonization/standardization (e.g., units, terminology, coordinate systems, data format…).

The relative importance of each of these steps and how they are performed (automatically, semi-automatically, or manually) and at what level (data originators, data initiative underpinning the thematic group, or the EMODnet thematic group partners themselves) depends on the thematic portal in question.

[8]More details about EMODnet data and data products can be found on http://www.emodnet.eu/data-portfolio
[9]http://www.europe-geology.eu/



Explanation of key European open source data integrators and service providers, financed by the EU

Copernicus Marine Service

CMEMS is the operational marine service component of the COPERNICUS program and is funded by DG GROW (Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs). It delivers generic and systematic information (observations and forecasts) on the physical state and dynamics of the ocean and marine ecosystems. CMEMS is composed by 3 main service layers: the central information, the dissemination unit and the production layers (composed by several production units that manage the production of observation and forecast products). One of the production units is the **In Situ TAC** – in situ thematic assembly centre – that is in charge of the collection and harmonization of near real time and delayed mode physical and biogeochemical oceanographic data. These data are used to feed models or to calibrate/validate the outcome of models of the others production units. The In Situ TACs also feed data into EMODnet Physics (see Section 6 for more details).

SeaDataNet

SeaDataNet is a pan-European data infrastructure for ocean and marine data management and is funded by DG RTD (Directorate-General for Research and Innovation). SeaDataNet community dates back to 1999 and was very much involved in the planning of EMODnet, now underpinning several EMODnet thematic groups: Chemistry, Bathymetry, Physics and to a lesser extent Biology. SeaDataNet data are derived from many different sensors installed on research vessels, satellites and in-situ platforms that are part of various ocean and marine observing systems and research programs. These different data are first assembled at distributed data centres interconnected by the SeaDataNet infrastructure. The data assembly centres are mostly **National Oceanographic Data Centres (NODCs)** which belong to major marine research institutes as well as international organizations such as IOC/IODE and ICES. These NODCs constitute an intermediate step between the data originators and SeaDataNet (see Table 2 and Section 6-7 for more details).

EMODnet

EMODnet is a long-term European initiative funded by DG MARE (Directorate-General for Maritime Affairs and Fisheries) that assembles and distributes marine data, metadata and data products spanning 7 thematic areas physics, bathymetry, geology, biology, chemistry, seabed habitat maps and human activities (see other sections of this paper for further information).

FIGURE 1 | EMODnet in the context of other European, regional and global marine data, and data product initiatives. For Europe, only three pan-European initiatives supported long-term by the European Union are included. This list is not comprehensive but provides some key examples. The Figure shows the flow of marine knowledge from original data (outer circle) to data services (middle circle) and to the users and societal benefits (center). The Figure does not aim to define the wide variety of data collectors and data providers which span academia and public authorities to industry. Data collection networks, systems, and initiatives are also nation and region-specific.

TABLE 2 | Thematic coverage provided by the data and products available through the EMODnet thematic portals.

BATHYMETRY	GEOLOGY	SEABED HABITATS	PHYSICS	CHEMISTRY	BIOLOGY	HUMAN ACTIVITIES
- Digital Terrain Model - Survey tracks and bathymetric survey data - Source references - Depth contours	- Seabed substrate - Seabed accumulation rates - Seafloor lithology, stratigraphy and fault maps - Coastal behavior - Geological events distributions - Mineral occurrences - Submerged landscapes* - Quaternary geology* - Geomorphology* - Boreholes locations* - Seismic tracks* *Upcoming products	Collection of point data from surveys - Broad-scale seabed habitat map - Environmental variables influencing habitat type - Collection of individual seabed habitat maps from surveys - Modeled maps of specific habitats - Composite data products	- **Wave height and duration** - **Sea temperature** - **Wind speed and direction** - **Salinity** - **Horizontal speed of the water column** - Water clarity - Changes in sea level - Inflow from rivers - Water conductivity /biochemical parameters - Atmospheric parameters - **Underwater noise**	- Acidity - Antifoulants - Chlorophyll - **Dissolved gases** - **Fertilizers** - Heavy metals - Hydrocarbons - Marine litter (micro, beach, seafloor) - **Organic matter** - Pesticides and biocides - Polychlorinated biphenyls - Radionuclides - Silicates	- **Phytoplankton** - **Zooplankton** - **Macro-algae** - **Seagrass** - **Fish** - **Reptile** - **Bird** - **Sea mammals** - Benthos - Functional traits - Introduced species - Protected species - Indicator species	- Aggregate extraction - Algae production - Aquaculture - Cables - Cultural heritage - Dredging - Environment - Fisheries - Hydrocarbon extraction - Main ports - Ocean energy facilities - Other forms of area management/ designation - Pipelines - Waste disposal - Vessel density - Wind farms

*Data products are free to access and use. In **bold**, data that match Essential Ocean Variables (EOVs).*

TABLE 3 | Main **data initiatives** (networks, projects, data management infrastructures…) data assembly centers (in italics) and data originators underpinning each of the EMODnet portals in Europe.

BATHYMETRY	GEOLOGY	SEABED HABITATS	PHYSICS	CHEMISTRY	BIOLOGY	HUMAN ACTIVITIES
SeaDataNet	**EGDI**	**MESH project[1]**	**CMEMS EuroGOOS-ROOS SeaDataNet**	**SeaDataNet**	**EurOBIS**	
National Oceanographic Data Centers (NODCs)			*In situ TACs NODCs*	*NODCs*		
National Hydrographic offices Research institutions OTHERS: e.g., Companies	National Geological Surveys	National agencies related to environment protection Research institutions	Agencies in the realm of operational oceanography Research institutions	Research institutions	Research institutions, public authorities, National Museums, Citizen science initiatives	Private and public data sources

[1] MESH Project: a marine habitat mapping programme supported by the EU's INTERREG IIIB fund.

In addition, each EMODnet thematic group analyses and processes the data to create products: maps, animations, profiles, trends, and others. The ways in which they each do this can also be quite different. Ultimately, the user can find and access these data products (as well as the data and metadata) in the thematic portals, with each portal presenting specific features, tools, and services. In the next sections, we will describe in detail all these components of the knowledge value chain for three EMODnet thematic groups: Physics, Chemistry, and Biology. The reader is invited to visit the remaining thematic portals for additional information.

EMODnet PHYSICS

Background

EMODnet Physics originates from the advances made by the GOOS (Global Ocean Observing System) community (especially the European component, EuroGOOS) in the development of physical operational oceanography capabilities.

OceanObs99 had a vision of a "*new era in oceanography, one where research and operational systems are mutually supportive and beneficial, and one where the rapid and wide distribution of information (data, methods and products) is* *accepted as preferred modus operandi*" (Busalacchi, 2009). Twenty years later, in spite of technological advancements, data management, integration, and consistency remain a challenge.

Facing that challenge, EMODnet Physics has developed a "federated" network infrastructure and provides a single point of access to near real-time (NRT) and historical *in situ* datasets, products, and their metadata of physical parameters of European Seas and global oceans. This "federated" network infrastructure links data originators and other marine data aggregating infrastructures.

Data Flow

In Europe, EMODnet Physics is strongly federated with three other data aggregating infrastructures: (1) SeaDataNet and its network of National Oceanographic Data Centers (NODCs), (2) EuroGOOS-ROOS (Regional Operational Oceanographic Systems), and (3) the Copernicus Marine Environment Monitoring Service *in situ* Thematic Assembly Center (CMEMS-*in situ* TAC). CMEMS-*in situ* TAC and EuroGOOS-ROOS are closely related and concern mostly the operational near real-time data flow, whereas NODCs provide historical validated data. EMODnet Physics is bridging the gap between both types of data streams.

SeaDataNet and CMEMS were described in **Figure 1**. EuroGOOS is an association of European agencies to further the goals of GOOS, and in particular the development of Operational Oceanography. EuroGOOS now has 42 members in 18 European countries. The EuroGOOS Regional Ocean Observing Systems (ROOS) are the core of the EuroGOOS association and are responsible for the collection of *in situ* data in the respective region. They feed near real-time data to both CMEMS and to EMODnet Physics. The CMEMS *in situ* TAC was developed on top of the EuroGOOS-ROOS concept and infrastructure.

EuroGOOS-ROOS, CMEMS-*in situ* TAC and SeaDataNet-NODCs are also integrated with other available sources beyond Europe. In this way, EMODnet Physics interacts with international data collection networks and programmes like JCOMMOPS (the Joint Technical Commission of Oceanography and Marine Meteorology *in situ* Observing Platform Support Center), which supports several IOC and World Meteorological Organization (WMO) programmes.

The collaboration between EMODnet Physics and JCOMMOPS has largely increased the platforms and data connected to the portal since its initial phase in 2010. Datasets acquired under the umbrella of international programmes such as Argo, DBCP[10] and GO-SHIP[11], are monitored by JCOMMOPS and made accessible via EMODnet Physics.

EMODnet Physics database is updated three times a day. There are three main NRT pathways to EMODnet Physics. The first route is via the EuroGOOS ROOSs and the CMEMS *in situ* TAC. This combined infrastructure is based on regional nodes which guarantee the same quality of the products delivered to the end-user. The second route collects and distributes data from international monitoring programs such as Argo, GO-SHIP, DBCP, etc., which are collected and organized by the Global Assembly Data Centers (GDAC). Data quality control is left to the responsibility of the data originators, who are required to use internationally agreed methods. The third route is via Thematic Assembly Centers (TACs) that are in charge for the collection and dissemination of "younger" platforms and parameters (e.g., sea surface currents fields recorded by HF Radars). For the three cases, operational platforms provide data time series as soon as data are ready—e.g., a fixed platform delivers data daily (at least), an Argo float delivers almost weekly.

Data transmitted in real time only undergo a "rough" quality control. They are provisionally included in the system, but eventually replaced by reprocessed data, submitted to a stricter quality control performed by NODCs. This replacement occurs periodically, but the time lag may vary depending on the type of platform/data network.

Dissemination of European historical validated data is organized in coordination and cooperation with SeaDataNet and the network of NODCs. The NRT data go through a stricter quality control before NODCs validate the datasets for long-term storage and stewardship. This validation process ends when the metadata of the processed dataset are published in a CDI (Common Data Index).

Moreover, EMODnet Physics portal provides data access to- and preview of- coastal data in non-European areas (e.g., NOAA platforms for the US and globally, International Arctic Buoy Programme platforms for the Arctic area, the Integrated Marine Observing System for Australia and others) and it provides regional stakeholders and international networks with tools to serve their users and communities.

After 10 years, EMODnet Physics can now boast global coverage (**Figure 2**), by incorporating data from supplementary physical monitoring systems: drifting buoys, gliders, and emerging measurement systems (e.g., HF radar, animal borne instruments, etc.). In total, it provides access to more than 160,000 platforms, and more than 800,000 datasets. All available data and metadata follow the same standards (CF Convention and Metadata[12] and SeaDataNet controlled vocabularies) and formats (e.g., NetCDF, csv).

Products

Besides data and metadata, EMODnet Physics also generates products that serve specific communities and stakeholders.

One example of EMODnet Physics products in collaboration with a Pan-European High-Frequency Radar Network (Rubio et al., 2017; Roarty et al., 2019) are sea-surface currents from high-frequency radars. Another example of a specific product under construction is river outflow, combining the geometry of the rivers, *in situ* data (very often water level and not water flux) and satellite observations.

Some products require collaboration with experts from different geographical regions. Since EMODnet Physics is federated with SeaDataNet and CMEMS, it can provide access to some of their products. For instance, SeaDataNet regional

[10] Data Buoy Cooperation Panel http://www.jcommops.org/dbcp/
[11] http://www.go-ship.org/
[12] http://cfconventions.org/

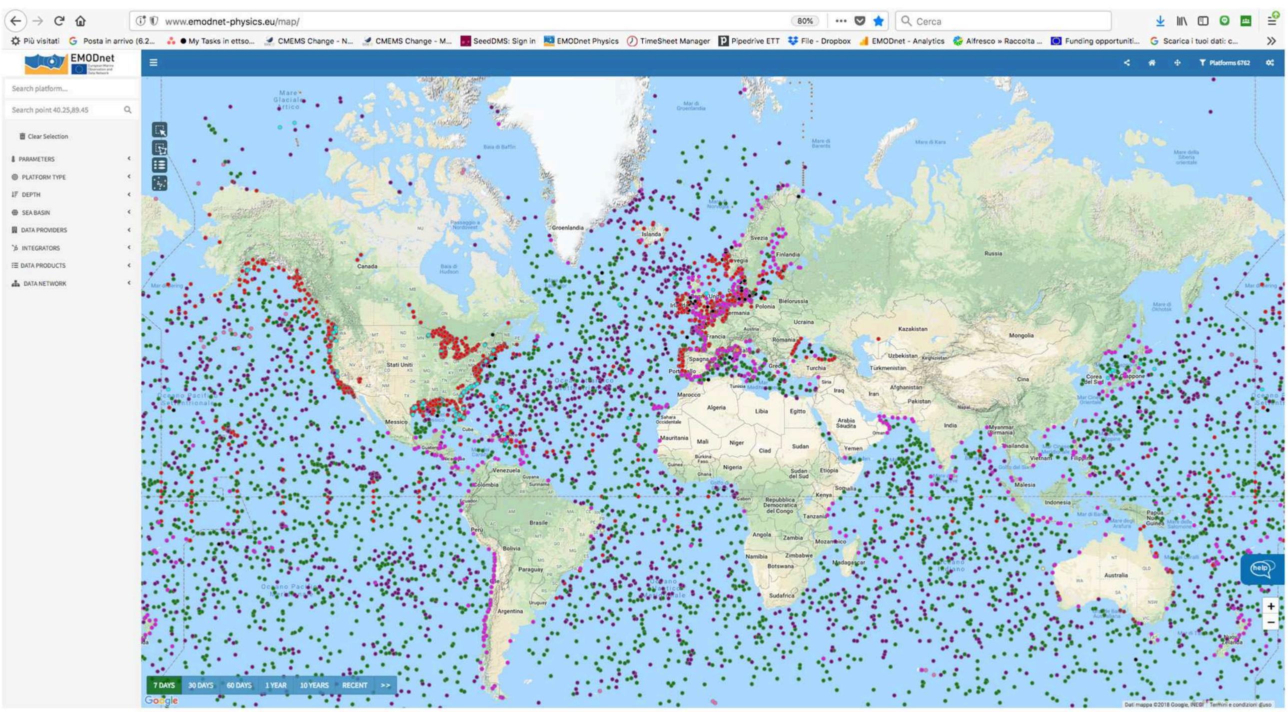


FIGURE 2 | 1Example of data accessible in EMODnet Physics during a 1 week period.

products such as temperature and salinity climatologies in the Arctic, Black Sea, Baltic Sea, the Mediterranean, North Sea, Atlantic-Iberian, and Biscay-Irish Sea are accessible through EMODnet Physics, with advanced sub-setting and discovering features. EMODnet Physics also provides access to gridded temperature and salinity from reprocessed data for the last century as well as ice coverage in the Arctic.

Another example concerns sea-level data and data products. By integrating more than 400 European tide gauge stations, 290 stations from the Global Sea Level Observing System (GLOSS) core network, and more than 1,300 stations from the Permanent Service for Mean Sea Level (PSMSL), EMODnet Physics is offering one of the widest *in situ* data collections for sea-level data. Based on the PSMSL collection, EMODnet Physics is making available maps of relative sea level trends, while absolute sea level maps are based on the SONEL product from the University of La Rochelle (France)[13].

Portal and Services

EMODnet Physics is continuously increasing the number and type of platforms in the system by unlocking and providing data from a growing number of data sources. For each connected platform, a dedicated platform page is available that provides the user with metadata, plots, download features, platform products (e.g., monthly averages or wind plots), additional information and links, as well as statistics on the use of the data from that specific platform. Data quality information is available in connection to datasets.

EMODnet Physics is developing interoperability services (**Table 4**) to facilitate machine-to-machine interaction and to provide other systems and services with ocean physical data and metadata from the European seas. A way to pursue this is through the continuous systems' update with new interoperability services, techniques (Open Geospatial Consortium-OGC, Sensor Web Enablement-SWE) and standards (ISO, NetCDF, IODE), in particular:

- Fixed stations: NetCDF format, SeaDataNet vocabulary, CF (Climate and Forecast) convention variable
- Argo: NetCDF format, SeaDataNet vocabulary, CF convention variable
- Surface drifter: Standards and data management established by JCOMM/DBCP
- Deep ocean observatories: FixO3 data policy (based on OceanSITES policy), NetCDF format and ASCII;
- Glider: Standards and data management of the EGO COST Action ES0904[14] and FP7 GROOM

On top of these common standards, EMODnet Physics develops and provides a further level of interoperability tools such as Web Map Service (WMS), Web Feature Service (WFS), REST/Simple Object Access Protocol (SOAP) web

[13]www.sonel.org

[14]https://www.ego-network.org/dokuwiki/doku.php

TABLE 4 | EMODnet physics interoperability machine to machine M2M services.

Service	Description	Examples
PermaURL	All platforms	http://www.emodnet-physics.eu/map/platinfo/piradar.aspx?platformid=10273 http://www.emodnet-physics.eu/map/platinfo/pidashboard.aspx?platformid=10273 Service description at: http://www.emodnet-physics.eu/map/spi.aspx
API REST/SOAP	Latest 60 days of data	www.emodnet-physics.eu/map/Service/WSEmodnet2.aspx
OGS WMS, WFS, WCS	Postgresql + Geoserver	geoserver.emodnet-physics.eu/geoserver/web examples and service description at: www.emodnet-physics.eu/map/service/GeoServerDefaultWMS.aspx www.emodnet-physics.eu/map/service/GeoServerDefaultWFS.aspx
THREDDS (OpenDAP, WMS, WCS)	Latest 60 days + HFR data + Ice	thredds.emodnet-physics.eu/thredds/catalog.html
ERDDAP	Latest 60 days	erddap.emodnet-physics.eu
Widgets	All plots	www.emodnet-physics.eu/Map/Charts/PlotDataTimeSeries.aspx? paramcode=TEMPplatid=8427timerange=7

services, THREDDS[15], and ERDDAP[16] catalogs, in order to make these data accessible, discoverable, and usable by a wider community. Interoperability services are provided by a GeoServer infrastructure that is OGC compliant. Plot widgets to embed a parameters plot/chart into an external portal are offered too.

To facilitate the use of the available services, documentation and details on available machine-to-machine interfaces are made available on github[17].

Data and data products are accompanied by metadata covering information on ownership, data quality, and data quality check procedures, as well as links to get additional information on methods used for their constructions. Common QA/QC protocols as well as best practices have been collected and made available through the Physics portal[18].

EMODnet CHEMISTRY

Background

EMODnet Chemistry's main purpose is to provide data and information relevant for the European Union's Marine Strategy Framework Directive (MSFD) (European Union, 2008), adopted in 2008 to set rules to protect more effectively the marine environment across Europe and to achieve Good Environmental Status (GES) by 2020. MSFD GES is defined by 11 qualitative Descriptors (and related criteria) that provide a detailed insight of the marine environmental status and its possible evolution. In addition, EMODnet Chemistry complies with the INSPIRE Directive (European Union, 2007/2/EC), which establishes rules for handling, accessing and sharing spatial information at European scale focusing on interoperability of spatial data sets and services.

EMODnet Chemistry places special focus on high-quality marine environmental data related to the MSFD GES Descriptor 5 (Human-induced eutrophication), Descriptor 8 (Concentrations of contaminants), Descriptor 9 (Contaminants in fish and other seafood), and Descriptor 10 (Marine litter) at a regional scale. The goal is to build a knowledge base to support the implementation of marine policies and foster sustainable development. Data relate to three matrixes (water column, sediment, and biota) and have recently extended to debris on beaches (nets, bottles etc.), on the seafloor (i.e., litter collected by fish-trawl surveys), and in the water column (floating micro-plastics).

EMODnet Chemistry is built upon SeaDataNet and its network of NODCs (see **Figure 1**; **Table 3**), adopting and adapting as necessary its standards, tools, and federated network of data resources.

Data Flow

The data flow within EMODnet Chemistry consists of a series of steps necessary to publish reliable and harmonized data and data products. The steps include, amongst others, assembly, quality control/quality assurance (QC/QA), and standardization. Interoperability and reliability are safeguarded through standardization and quality control procedures, carried out after data collection.

A network of NODCs distributed across many countries performs the data assembly. At the national level these NODCs supervise the provision of environmental data from research and monitoring activities, maintain regular contact with data originators, and complement data with the best available metadata to ensure reliability. The direct link with the data sources ensures that the best sets of measured data and associated metadata are stored with a commonly agreed data policy.

Data originators are responsible for the first quality control of data and flagging with quality information. Within EMODnet Chemistry, a data validation loop was developed to highlight possible data inconsistencies in the distributed infrastructure in close contact with data originators. As a first step of this loop, data are checked and completed with a standard set of metadata. A set of QC are applied to ensure e.g., that geographical position and time of data are realistic and to compare measurements with broad ranges and specific regional ranges. Whenever available, data are also compared with climatologies. As a result, all data

[15]THREDDS Catalogs are logical directories of on-line data resources, encoded as XML documents, which provide a place for annotations and other metadata.
[16]ERDDAP is a data server that provides a simple, consistent way to download subsets of scientific datasets in common file formats and make graphs and maps.
[17]https://github.com/EMODnet-Physics/EMODnet-Physics-Documentation
[18]http://www.emodnet-physics.eu/portal/bibliography

are archived with a quality flag value that provides information on their reliability. Data are then aggregated at basin scale (grouping different analytic terms used by data originators into a unique aggregated term with a unique measurement unit) and further quality controls are performed at regional level following a common approach. The main goal of this activity is to obtain homogeneous regional datasets (e.g., a unique dataset of phosphate concentration in the water column starting from different datasets of phosphate concentration expressed with different units) that could be used to generate homogeneous data products. The results of the regional quality control are sent to the NODCs to correct errors or anomalies in the original copy of the data available in the EMODnet infrastructure. This feedback loop guarantees a continuous data quality upgrade.

Standardization is implemented at two main levels: syntactic and semantic. The former is achieved through provision of common formats for metadata and data files; the latter with the adoption of a set of vocabularies that become a common language to describe data and metadata over time, collected by diverse projects and in different countries. EMODnet Chemistry metadata are stored in the XML ISO 19139-19115 standard, and make use of a set of common vocabularies to ensure interoperability[19]. Data are stored in Ocean Data View (ODV) format, a simple comma-separated value format including quality information for each parameter.

Once all those steps are accomplished, EMODnet Chemistry generates customized products and provides data sharing services in line with the policies defined by data originators. Products generation enables to analyze and re-aggregate data to build knowledge from raw data.

Data usage is managed according to the SeaDataNet Data Policy, which includes a range of access conditions from open access (SeaDataNet license) to negotiable. The latter is used by a small percentage of data originators in cases such as during a moratorium period, or when the data are especially costly (e.g., seismic survey data), or sensitive (e.g., contaminants in seafood data). Furthermore, the SeaDataNet Data Policy contains a disclaimer and an obligation for users to acknowledge data originators in their use cases. Thanks to the mutual trust between data originators and the NODCs, originators are increasingly willing to release their restricted datasets for use in the construction of EMODnet data products. At the same time, data originators are progressively encouraged to share their data more openly and under the SeaDataNet license.

Management of marine litter data is a recent addition to the infrastructure. The topics of interest are beach litter, seafloor litter and floating micro litter. In Europe, the development of the management systems for the three debris categories are different in terms of observation instruments, policies, and degree of development (regional, national…). The data management plan was to adopt consolidated data formats when available and adapt them when needed. Following this, three specific approaches have been adopted, using the best available reference documents to develop a tailor-made approach at European scale.

For beach litter, the approach is based on the OSPAR (Convention for the Protection of the Marine Environment of the North-East Atlantic) experience and opens the possibility to report data using OSPAR, MSFD, UNEP (United Nations Environment Programme)/MAP (Mediterranean Action Plan), and UNEP Marlin (Baltic marine litter project Marlin-Litter monitoring and Raising awareness 2011–2013) categories.

For bottom trawl litter in Europe, there are two main consolidated data collection protocols since several years. One is adopted in the North/Western part of Europe -ICES DATRAS (Database of Trawl Surveys), while the other is adopted in the Mediterranean area [MEDITS (Mediterranean International Trawl Survey)/UNEP/MAP MED POL programme[20]]. The EMODnet Chemistry approach followed the ICES DATRAS experience, but it is possible to report data using ICES, MSFD or MEDITS categories.

For floating marine micro-litter, the SeaDataNet formats (CDI and ODV) were adopted and adjusted following comparison with other available European information. Data collection for marine litter is done through already existing regional data bases (OSPAR/MCS for beach litter, ICES for bottom trawls) or through the network of NODCs.

Products

As stated earlier, EMODnet Chemistry has developed with the aim to become a major support tool for the assessment of marine environmental status under the MSFD. In addition to data, EMODnet Chemistry delivers data products related to MSFD Descriptor 5, 8, 9, and 10.

When developing European-scale products, comparability and harmonization of approaches must be assured, while respecting the peculiarities of each marine region. Regional and combined interpolated data maps are available based on DIVA 4D 10-year analysis. DIVA stands for Data-Interpolating Variational Analysis (Troupin et al., 2012). It is a software for spatial interpolation of *in situ* data to generate gridded fields, which uses an efficient finite-element method. DIVA works with a variational inverse methodology to derive a continuous field starting from discrete observations. DIVA basin maps have been developed only for nutrients with good data coverage (**Figure 3**). Considering that EU Member States must perform reporting under the MSFD on a 6 year cycle basis, new regional maps with a 6 year moving window are under development for the parameters silicate, phosphate, chlorophyll, oxygen, and Dissolved Inorganic Nitrogen (DIN).

Additionally, regional validated data collections for "eutrophication-related" parameters are being prepared and made available to the European Environmental Agency and to any other possible users.

For contaminants, spatial coverage is fragmented and there is a large heterogeneity in the data from monitoring. In 2018–2019, maps of contaminants have been generated and will be

[19]SeaDataNet DATA QUALITY CONTROL PROCEDURE https://www.seadatanet.org/content/download/596/3118/file/SeaDataNet_QC_procedures_V2_(May_2010).pdf?version=1

[20]The MED POL programme is the marine pollution assessment and control component of MAP.

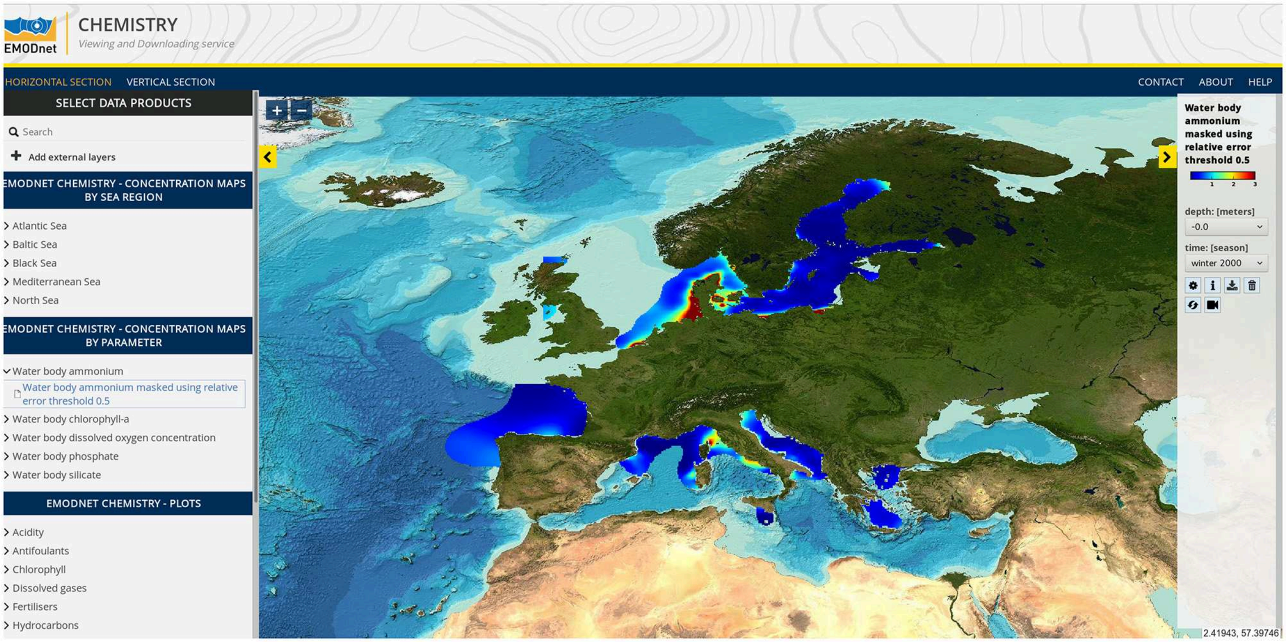


FIGURE 3 | Products: global interpolated maps for Ammonium in the water column, winter 2000.

presented to the board of experts for validation. Harmonized and aggregated data collections for the contaminants have been equally produced and will be available through the web portal in 2019.

Litter is a new topic for EMODnet Chemistry and so are its products. Litter data and their coding systems for quantification are very heterogeneous so their aggregation into products will be a challenge. First data analyses and basic outlines have been produced; even simple visualizations of a whole European dataset can be useful tools for managers. Maps of the surveys for beach and seafloor litter were published recently (March 2019). They highlight the differences between the litter reference lists and gears used along the European coasts (**Figure 4**).

Beyond 2019, the objective is to take advantage of the valuable information in a harmonized litter database to create a variety of products tailored to different stakeholder requirements.

Portal and Services

As for the other EMODnet portals, the EMODnet Chemistry portal[21] has dedicated services to access metadata, data, and products. Metadata and data are accessible through the CDI data access interface, while products are accessible using the viewing service (Ocean Browser) and the product catalog (Sextant). Metadata and products are always freely available.

- The CDI data access interface provides a service to search and browse what is available. There are several search criteria to filter out the available information (free text, parameter, spatial coverage, period covered, data originator, and others). A specific version of the interface named "Search Chemicals by Region" plots the regions of interest against the available parameters, so as to provide quicker access. Data are available in the following formats: ODV, NetCDF, or Medatlas. Registered users can freely access unrestricted data, while a negotiation process moderated by the relevant NODC is necessary for restricted data[21].
- The Ocean Browser viewing service provides access to the available products. Products are provided in OGC-compliant formats (WMS, WFS, Web Processing Service WPS) to ensure interoperability. The product viewing service provides access to interpolated maps (WMS layers) and dynamic plots generated on the fly (WPS) from the validated data buffers.
- Sextant is a catalog compliant with OGC/Catalog Service Web (OGC/CSW) protocol and provides facilities to search and access the EMODnet Chemistry products (interpolated maps for each EU sea-basin, interpolated maps combining all the EU sea-basins, validated, aggregated, and harmonized data sets). All the available products are described and continuously updated in Sextant. Digital Object Identifiers (DOI) have been attributed to each of the products and the related landing pages have been published with download and viewing links.
- Furthermore, web portal hosts a page with detailed information on the available web services in order to facilitate M2M interaction[22].

[21] www.emodnet-chemistry.eu/data

[22] www.emodnet-chemistry.eu/products/api

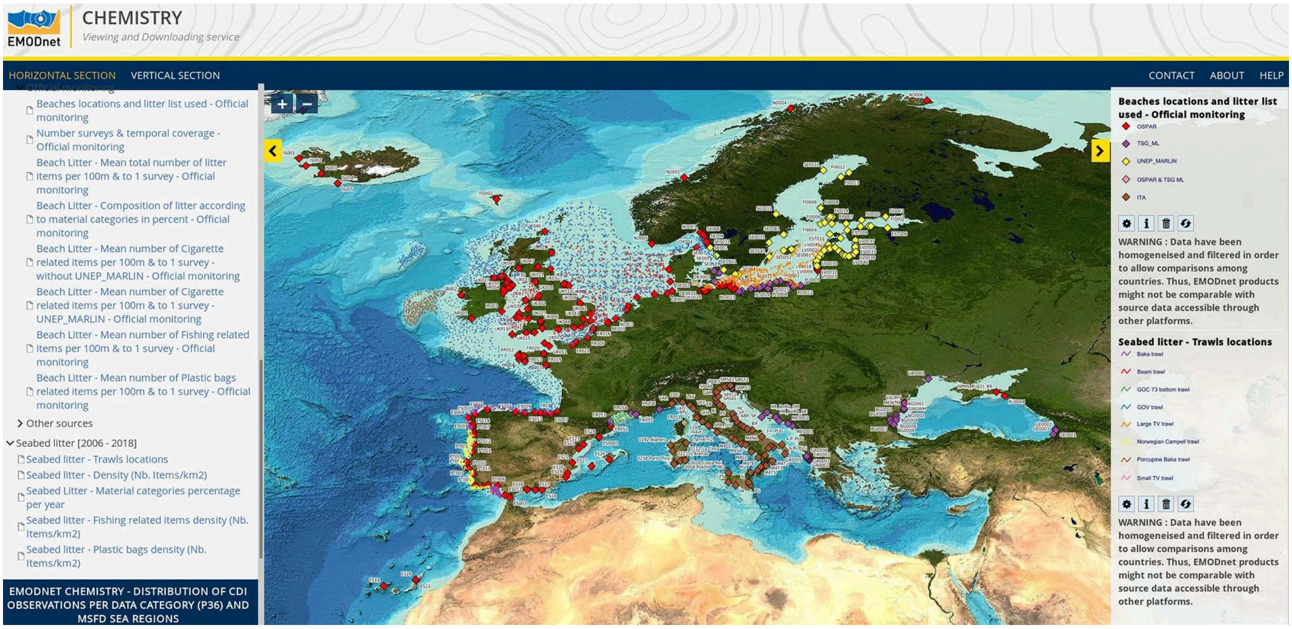


FIGURE 4 | Map showing the spatial distribution of the European surveyed beaches (monitoring sources) and European trawls locations highlighting the differences on the litter reference list and trawling gears used (March, 2019).

EMODnet BIOLOGY

Background

Marine biodiversity data are essential to measure and study the ecosystem health status of maritime basins and their trends in time. In the ocean, overfishing and other threats (such as pollution and eutrophication, climate change, habitat fragmentation, alien species, or mining activities) have reduced species' populations and have altered ecosystems, reducing their capacity to generate food resources and many other services for humankind. Furthermore, many species of mammals, birds, reptiles, and fish are in danger of extinction. In a time of global change and biodiversity loss, species observations over time are crucial for species inventories, as inputs to ecological models and for future predictions of change.

In marine biology, a large variety of methods have been used to sample marine species, including visual observations, water samples, nets, hooks, traps, grabs, sediment collection, acoustic observations or bio-optics. Various methods and metrics have been used to characterize the relative abundance of species, including numbers of individuals, surface cover, and/or biomass within samples. Furthermore, marine biodiversity data are often collected with limited spatial and temporal scope in small datasets for a specific species group or habitat and are scattered over different research institutes, governmental organizations and private companies in European and non-European countries bordering the European seas. Therefore, there is a continuous need to assemble these individual datasets, and process them into interoperable data formats for assessing the environmental state of overall ecosystems and complete sea-basins.

EMODnet Biology disseminates information about marine species in European waters including observations of phytoplankton, zooplankton, angiosperms, macro-algae, benthos, marine mammals, marine reptiles, birds, and fish. The project produces digital data products allowing analysis of changes in species abundance and extent over time and space. The taxonomic standard used in EMODnet Biology are based on the World Register of Marine Species (WoRMS), the authoritative and comprehensive global list of names of marine organisms. Geographical units are standardized to marineregions.org geo-objects and additional biotic or abiotic measurements are mapped using controlled thesaurus from the Natural Environment Research Council (NERC) Vocabulary Server maintained by the British Oceanographic Data Center (BODC). Through the implementation of the European Ocean Biogeographic Information System (EurOBIS) as marine biological data infrastructure of EMODnet Biology, data are processed following the Darwin Core Archive, an internationally recognized biodiversity informatics data standard that simplifies the publication of biodiversity data. EurOBIS has a strong collaboration with the Ocean Biogeographic Information System (OBIS), an evolving global strategic alliance of people and organizations sharing a vision to make marine biogeographic data, from all over the world, freely available over the World Wide Web. OBIS is the world's largest database on the diversity, distribution and abundance of marine life.

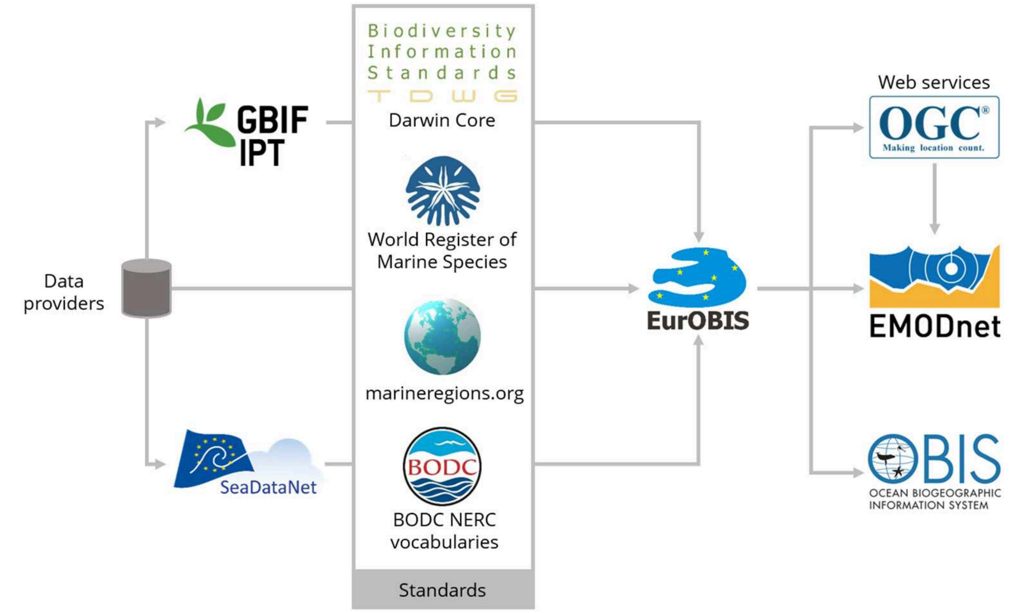


FIGURE 5 | Representation of data flow used within EMODnet Biology.

Data Flow

EMODnet biology uses the EurOBIS data system to harmonize and centralize biogeographic data on marine species collected by European institutions (**Figure 5**). The data that flows to EurOBIS is being mapped to the Darwin Core Terms. The purpose of these terms is to facilitate data sharing by providing a well-defined standard core vocabulary in a flexible framework to minimize the barriers to adoption to ensure interoperability and to maximize reusability.

EurOBIS receives its data through different pathways:

- Data providers can set up an Integrated Publishing Toolkit (IPT)-instance to serve their data in Darwin Core Archive Format (DwC)
- Individual providers can provide their data in Biological ODV format and serve through the SeaDataNet infrastructure, which is semi-automatically mapped with Darwin Core
- Individual providers can send their data to EurOBIS by email or as a service in different formats which are manually mapped to the Darwin Core
- In addition, the two European sub-nodes—OBIS Black Sea and MedOBIS—provide their data to EurOBIS, thus capturing all the marine European data in one system.

EurOBIS is in close communication with OBIS-SeaMap. OBIS-SeaMap—the Ocean Biogeographic Information System Spatial Ecological Analysis of Megavertebrate Populations—is a spatially referenced online database, aggregating marine mammal, seabird, and sea turtle observation data from across the globe. Datasets from OBIS-SeaMap containing European data are also made available to EMODnet users.

EurOBIS acts as the responsible node to make these data available to the OBIS community and in turn publishes the data through the OBIS database. Data that contribute to EurOBIS and OBIS are subject to a series of quality control steps, including for taxonomic nomenclature, and geographical location.

Products

EMODnet Biology produces digital data products allowing analysis of changes in species abundance and extent over time and space (**Figure 6**). This work was initiated with the development and production of gridded map layers from different data sources showing the average abundance of several species per functional species group for different time windows (seasonal, annual, or multi-annual) using geospatial modeling. These products are being expanded by: (1) integrating biological trait information to calculate spatial products for biological indicators (vulnerable vs. sensitive benthic communities, invasive species); (2) compiling historical data that can be used for reconstruction of long-term trends for some selected groups; and, (3) integrating environmental data layers that can be used as the basis for Species Distribution Models.

Portal and Services

The EMODnet Biology Portal[23] allows public access to and viewing of data, metadata, and data products of marine species occurring in European marine waters. It offers different services including:

- Data Catalog—The data catalog is the easiest way to access nearly 1,000 datasets available through EMODnet Biology. The catalog contains information on the where, when, what, how, and who of the different datasets, using ISO19115-compliant metadata descriptions. Datasets can be filtered by multiple

[23] www.emodnet-biology.eu

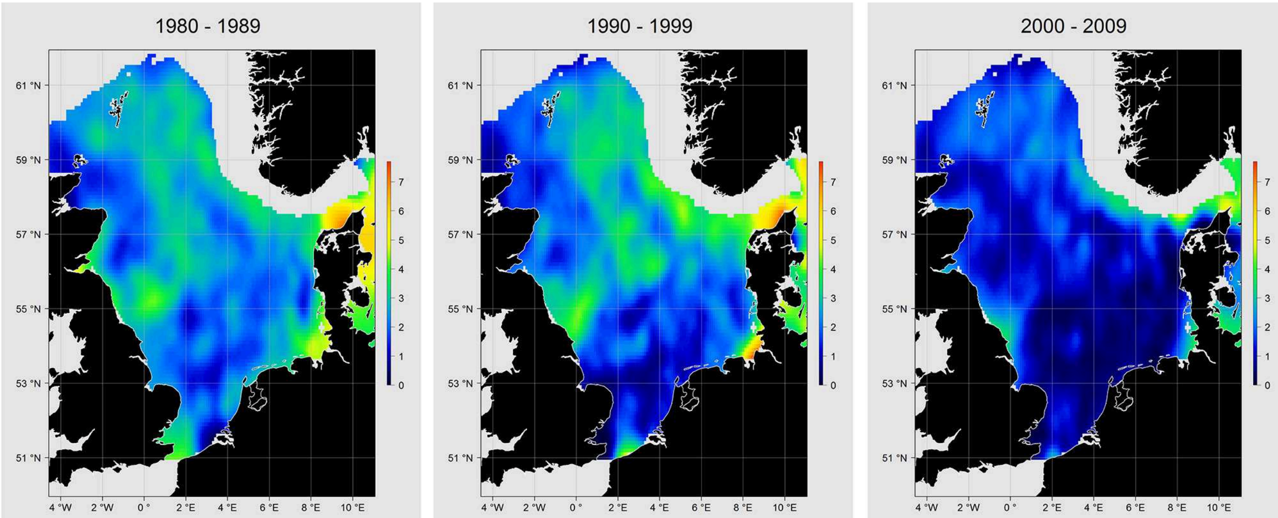


FIGURE 6 | Production of gridded map layers using geospatial modeling, showing the average abundance of Cod (Gadus morhua) in the North Sea showing stock depletion. Scale: log-transformed CPUE.

parameters via the advanced search from taxon, to institute, to geographic region. Each of the resulting datasets then links to a detailed fact sheet containing a link to original data provider, recommended citation, policy, and other relevant information. Most datasets have a CC-BY[24] license.

- Data Download Toolbox—The data download toolbox allows the users to filter and select data through a step-wise approach, e.g., perform predefined geographic and temporal selections, add specific taxonomic or functional filters, select data with a certain quality and precision or that contain additional measurements beyond occurrences. A data file will be generated that can be downloaded as a csv-file or can be accessed via a WFS web service. The query itself can also be stored as a JSON-file.
- Map viewer—The data portal allows users to search for datasets by species list (e.g., benthos, fish, algae…) and by both scientific and common name. The selected taxon can be plotted in an integrated map viewer, which includes administrative and environmental layers that can be toggled on and visualized simultaneously.
- Atlas of Marine Life Data—In this section of the portal, products are structured around the EOVs for Biodiversity. Data products can be visualized and product stories have been created to display detailed information on the scientific rationale for each product, a link to the underlying datasets, a description of the methodology and a link to access the code and workflows.
- Web Services—All species occurrence data (species observations) are available as WFS as are additional measurements linked to the occurrence. The gridded abundance data products are available as WFS/WMS.

[24]https://creativecommons.org/licenses/

THE OTHER EMODnet STRANDS

EMODnet's Sea-Basin Checkpoints

User requirements are a priority for EMODnet, so a series of "Sea-basin Checkpoints" were established, starting with the Mediterranean and North Sea in 2013 and extending to the Arctic, Atlantic, Baltic Sea, and Black Sea in 2015. These aimed to assess whether the observation networks, surveying strategies, and data access met users' requirements in those six regional European sea-basins.

The concept of EMODnet Sea-basin Checkpoints was introduced within the Green Paper "Marine Knowledge 2020: from seabed mapping to ocean forecasting" (European Commission, 2012). In spite of EU initiatives such as EMODnet, CMEMS and the Data Collection Framework (DCF) for Fisheries, that aimed to deliver seamless layers of marine data across national boundaries, there are still shortcomings with the availability and accessibility of EU marine data. Furthermore, there was no overall view of the priorities for further data collection or assembly. The EMODnet Checkpoint initiative was the first of its kind to begin to link all existing monitoring data at the level of the sea-basins and assess them in order to provide advice for future improvements to Europe's observation capacity, as well as identifying significant bottlenecks restricting wider data availability.

For each of the sea-basins, the teams working in the Checkpoints acted as surrogate users attempting to address a number of challenges (see **Table 5** for details about the expected outputs). The outputs of the challenges were then reviewed by panels of stakeholders and translated into reports that assessed the adequacy of the data, in terms of what is available and how fit–for-purpose it is, bearing in mind the particular challenge they were undertaking. Each of the six Sea-basin Checkpoints teams have approached these assessments using different methods, always striving to maintain the user perspective (see Pinardi et al.,

TABLE 5 | Description of the challenges that the checkpoints had to attempt with their corresponding expected outputs.

Challenge	Description of outputs
Wind farm siting	Determine the suitability of sites for development of a wind farm. All aspects should be considered: wind strength, seafloor geology, environmental impact, distance from grid, shipping lanes—even if one of the factors makes this a no-go scenario.
Marine Protected Areas (MPA)	Analyze the existing network of marine protected areas and: (i) categorize them according to the classification used by the International Union for Conservation of Nature; (ii) determine whether the network constitutes a representative and coherent network as described in article 13 in the Marine Strategy Framework Directive; (iii) determine how they are likely to be affected by climate change.
OilPlatform Leak	The contractor will be informed that there is a leak from an oil platform at a time to be decided by DG MARE. The contractor will not receive an advance warning of the exercise. The contractor will determine the likely trajectory of the slick and the statistical likelihood that sensitive coastal habitats or species or tourist beaches will be affected. The contractor will indicate what information can be provided within 24 and 72 h.
Climate	Determine: - change in average temperature at surface, 500 m depth and bottom on a grid, over the past 10 and 50 years - time series of average annual temperature at sea surface and bottom - time-series of average annual internal energy of sea - average extent of ice coverage over the past 5 years, past 10 years, past 50 years, past 100 years plotted on maps - total ice cover in sea (kg) over the past 100 years plotted as time series.
Coasts	Determine: - In the coasts of all coastal states, the average annual sea-level rise per stretch of coast (absolute and relative to the land), and for 10, 50, and 100 years. This should be provided in tabular form and as a map layer; - In the coasts of all coastal states, average annual sediment balance (mass gained or lost per stretch of coast) for 10, 50, and 100 years. This should be provided in tabular form and as a map layer.
Fisheries management	Produce tables for the whole sea-basin of: (1) mass and number of landings of fish by species and year; (2) mass and number of discards and bycatch (of fish, mammals, reptiles, and seabirds) by species and year.
Fisheries impact	Produce data layers (gridded), showing the extent of fisheries impact on the sea floor, in particular estimate: (1) area where bottom habitat has been disturbed by bottom trawling (number of disturbances per month); (2) change in level of disturbance over the past 10 years; (3) damage to sea floor to both living and non-living components.
Eutrophication	Produce data layers (gridded) showing: (1) seasonal averages of eutrophication in the basin for past 10 years; (2) change in eutrophication over the past 10 years.
River inputs	For each river bordering the sea-basin, a time series of annual inputs to sea of: - water (mass and average temperature) - sediment - total nitrogen - phosphates - salmon - eels
Bathymetry	Sea-basin digital map of: - water depth - contour map of water depth for sea-basin in vector format in interval of 100 m, including coastline priority areas for surveying for safer navigation taking into account emerging needs - uncertainty in water depth for Black sea-basin
Alien species	Table and digital map of alien species in the sea-basin: species name - family (fish, algae, mammals, sponges etc.) - year of introduction - season for introduction (climate change, ballast water discharge etc.) - geographical area - impact on ecosystem and economy

2017 for a description of the method used in the Mediterranean). This user-oriented view makes this exercise unique and original, facilitating the development of more tangible recommendations for the future development of Europe's ocean observing framework and its evaluation. Pearlman et al. (2019, this issue) considers the checkpoints as "*the first community-based best practice for monitoring systems that incorporates end-user products.*" Also in this issue (Buck et al., 2019), highlights the checkpoints as an example of data democratization, where there "*the user defines the way the information derived from data is converted to knowledge.*"

The products listed in the challenged areas could not always be generated (in requested quantity and quality) due to different reasons:

- Data do not exist: this was generally related either to gaps in coverage (certain areas were not sampled) or insufficient resolution (the sampling density was not enough for the application pursued).
- Data exist but are not available: this can happen when the data cannot be found easily, or even if they are found there are restrictions of access. This can hinder fulfilling the challenges in a reasonable time or under a certain cost.

- Data exists but are not appropriate for the use: this can encompass many characteristics like timeliness, accuracy, precision, completeness, update frequency of the series or the type of format (more or less standard).

A summary of the main findings and suggestions is presented in **Appendix A1**. More information about the outputs of the challenges and the results of the assessments is available through a number of websites that can be accessed through the EMODnet Central Portal[25].

All Checkpoints have put in place management systems that identify which datasets have been used for each challenge and how those datasets have been assessed and used to create the products. This allows for repeatability and traceability of the assessment results. This monitoring assessment framework could be used periodically (a 3–5 year cycle was suggested) and turn into a "Checkpoint service," with the inclusion of new challenges and the development of new products depending on needs (blue growth, climate, environmental policies).

Data Ingestion

Over the past years, EMODnet has made huge advances in facilitating access to data from many sources. However, data still remain hidden or unusable because data holders lack the resources to share their data, due to restrictions in terms of resources, available time or technical know-how. EMODnet's Data Ingestion facility tackles these problems, by reaching out to data holders and offering a support service to assist them in releasing their data for subsequent processing and quality control and ultimately publishing as open data.

Key targets of the data ingestion service are organizations from public, research, and private sectors who are managing marine datasets for bathymetry, geology, physics, chemistry, biology, seabed habitats, and/or human activities and who are not yet connected and contributing to the existing marine data management infrastructures. The service aims to motivate and support those potential data providers to release their datasets for safekeeping and subsequent free distribution through EMODnet. The Ingestion portal provides services for submission, publishing, and guidance. The life-cycle of a data submission is divided into two phases:

- Phase I: from data submission to publishing "as is";
- Phase II: further elaboration and integration (of subsets) in national, European, and EMODnet thematic portals.

The EMODnet network for validating and processing data submissions is recruited from the EMODnet Ingestion and EMODnet thematic portal consortia and at present comprises circa 50 qualified data centers for marine chemistry, physics, geology, bathymetry, biology, seabed habitats, and human activities data. Active marketing and promotion toward potential data providers with banners and animation is ensured through the EMODnet Central Portal and thematic portals, as well as during conferences and workshops. On top of that there is national marketing undertaken by the EMODnet Ingestion ambassadors. This includes reaching out to their local networks of contacts, organizing national EMODnet days to build relationships, and distributing promotional media.

[25]http://emodnet.eu/checkpoints

Central Portal

The EMODnet Central Portal was implemented to centralize information about EMODnet. It is a single-entry point to data, metadata, and data products made available by the 7 EMODnet thematic portals as well as a gateway to the other EMODnet strands (Checkpoints and Data Ingestion). The EMODnet Central Portal also offers its own user-oriented data services comprising a geoviewer, a metadata catalog, a query tool and documentation on how to access data and data products using web services. The geoviewer provides access to over 40 different data products, in combination with additional data layers and administrative units, all of them based in OGC web services. Together with the metadata catalog, these services allow a wide range of professional users and general public to explore and visualize what EMODnet has to offer, with direct links to the original data and data products on the thematic portal webpages. The ongoing documentation on web services and data access is intended for data scientists or scientists with a strong data analysis background, as well as programmers, to help them understand how to access and analyze the data, create workflows or build applications using EMODnet data and web services. Finally, the query tool is aimed at marine spatial planners and/or practitioners, who would like to retrieve processed information from multiple thematic data products via one single interface in order to get a summary overview of a marine area under assessment. The EMODnet Central Portal works in close cooperation with the thematic lots and the EMODnet Secretariat to implement best practices which improve inter-operability of the data services and improve the user experience and uptake.

EMODnet Central Portal has become a powerful tool to communicate and disseminate information about EMODnet. The Central Portal website has regularly updated sections such as "News Flash," "Events," and "Use Cases" sections, which give visibility to EMODnet achievements and demonstrate their impact (**Figure 7**).

EMODnet AS A USER-ORIENTED SERVICE

EMODnet has transformed over the years from a bottom-up initiative developed largely from data provider communities to a more user-oriented service. The uptake and use of EMODnet data products and services by a wide range of users lie at the heart of assessing the success of the programme, and is central to the current range of activities. Through the (1) identification of the stakeholders and use cases and (2) the engagement with key stakeholders, EMODnet can work toward products and services that can be truly considered "essential."

EMODnet thematic groups report quarterly on a set of progress indicators that include, amongst others, number of visitors including their sector of provenance (distributed into four categories: Academia/Research; Government/Public

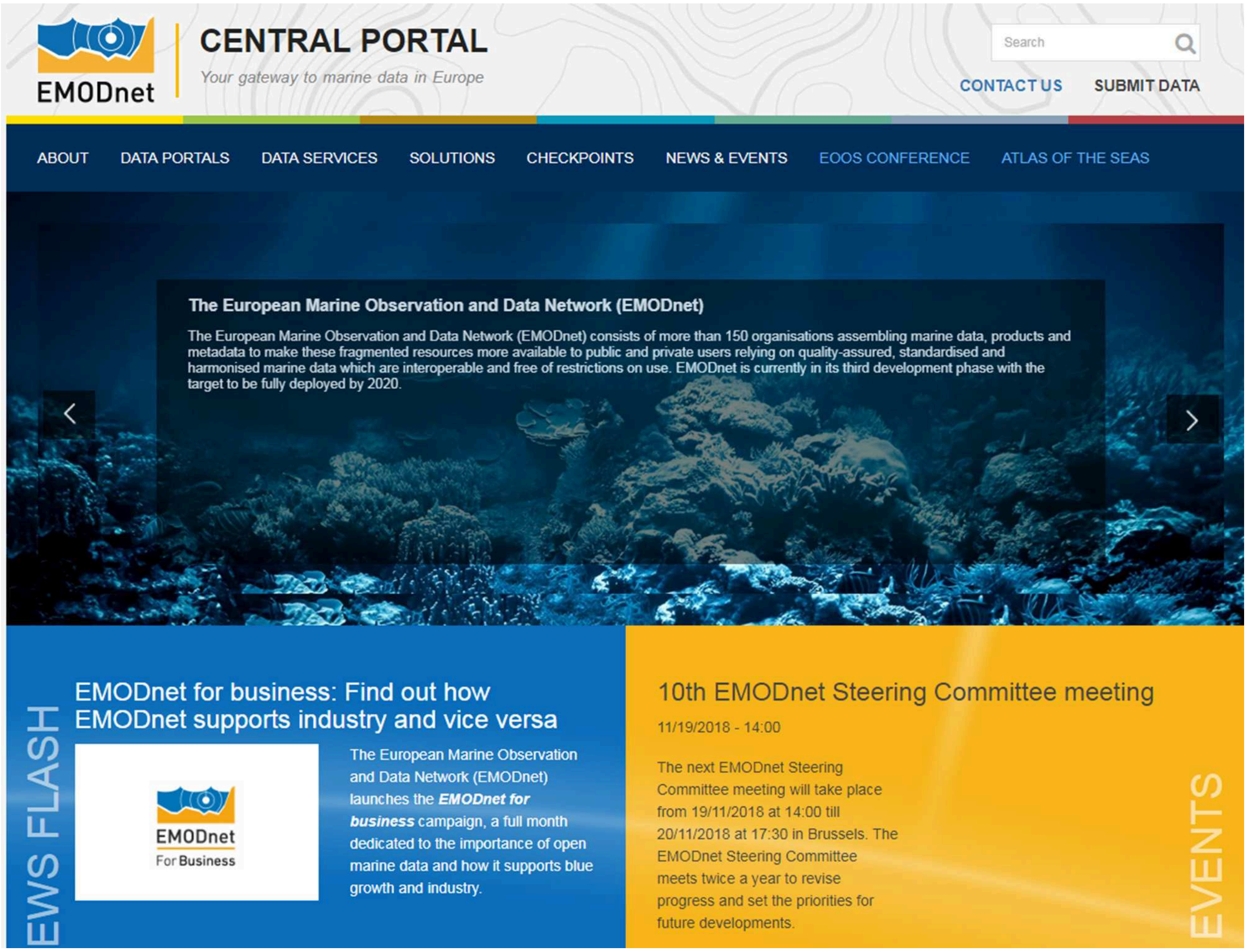


FIGURE 7 | Entry page of EMODnet Central Portal website providing a unified access to all EMODnet resources.

Administration; Businesses & Private; NGOs/Civil Society), as well as the main applications for the data/data products downloaded. From these indicators it is clear that academia and researchers constitute the main share of EMODnet visitors for all the thematic portals alike. However, the difference between this category and the others can be vary considerably. For instance, according to the report of the last quarter of 2018, 90% of Biology portal users identified themselves as belonging to research/academia while the other three main sectors were negligible. However, up to 25% of Geology and 30% of Human Activities users belonged to the private sector, whereas 30% of Chemistry users identified themselves as coming from an NGO or the Civil Society. In the same report, the percentage of users belonging to Government/Public Administration ranged between 5 and 15% (except for Chemistry, where the share was 21%).

Reported applications reflect the multidisciplinary nature of the EMODnet portfolio and reveal its high potential. Not surprisingly, many of the uses are research related, e.g., development of, validation of or comparison with other data or models of all kinds (species distribution modeling, wave modeling, tsunami modeling…); input data and/or support for presentations in the framework of lectures, MSc theses, and PhD dissertations. Other uses are related to the private sector, e.g., in the framework of prospection projects such as wind farming, cable routing or dredging. Studies supporting Marine Spatial Planning or Marine Protected Areas management (Government/Public Administration) are also mentioned.

In addition to that, EMODnet Secretariat collects and documents use cases that show how the EMODnet service has been used by industry, public authorities, researchers and civil society. These use cases are published regularly on the Central Portal webpage[26] classified by EMODnet theme and sector.

Whilst the requirements for what is considered an "essential" data product vary from region to region and at different geographic scales, the process for stakeholder engagement remains the same. It is critical that the development of data products is end-user driven, answering specific questions or

[26]http://www.emodnet.eu/use-cases

addressing existing gaps in knowledge. EMODnet groups have engaged with users since the beginning through different means. Surveys and questionnaires are regularly used to collect information from users, especially when planning portal updates, both in terms of content, type of products offered, and design. The feedback received has helped the EMODnet portals to progressively implement new tools that allow for a better user experience when accessing data, metadata, and products.

Engagement with individual users of the portals is also done via the Helpdesk service that is available in each of the EMODnet thematic portals. With this service, visitors to the portals can receive fast support in their searches and general navigation through the portals.

Workshops are also valuable tools to ensure that stakeholders views are captured, and that those stakeholders can suggest further product developments. For example, in 2017 the EMODnet Biology group trialed an approach to ensure the wide range of stakeholder views and requirements was captured, whilst ensuring that the global context was inherent within the process. An international workshop drew on the expertise of a wide range of practitioners actively involved in the coordination and management of marine biodiversity. Representatives from four European regional seas were present, participants from transatlantic and global partnerships, industry, conservation, and management bodies to discuss the development of a core set of data products to be delivered through EMODnet Biology. Participants were invited to identify existing gaps in data products and to highlight the types of data and information they required. The range of responses across stakeholders clearly indicated that the development of generic, or single-use data products were unlikely to meet the complex requirements of the varied stakeholders.

Not only are those who use EMODnet resources important stakeholders. Engaging with data providers is obviously also fundamental. As mentioned in the introduction, visibility of data ownership is one of the core principles of EMODnet so that the work of institutions collecting and processing data can be properly acknowledged. Specific examples of this engagement can be found via tracking tool like the ones offered by EMODnet Physics. Data providers receive reports by email informing them about the use (number of hits, most viewed datasets etc.) of their platforms/datasets on the EMODnet Physics portal.

In other cases, most of its efforts are concentrated in meeting the needs of one specific group of customers. This is the case of EMODnet Chemistry, for whom public European institutions, and even more those related to MSFD implementation are their preferential target user. To achieve this challenging goal, a tight connection with EEA, Regional Sea Conventions (OSPAR, HELCOM, Black Sea Commission, and MED POL), JRC and ICES has been established, and regular meetings are held. Online workshops with groups of MSFD experts have been carried out to identify needs focused on eutrophication, contaminants, and litter.

Participation in external events and business conventions as well as organizing specific user-oriented activities such as the EMODnet hackathon series called Open Sea Lab[27] are another way of collecting relevant information from users to understand what is working well, what gaps exist, and what barriers remain for users to fully exploit the available resources. Another way to engage more organizations is by broadening the Network itself. For this reason, the Secretariat created the EMODnet Associated Partnership scheme in 2017 for interested organizations to join without heavy administrative or contractual arrangements to allow EMODnet to grow as an inclusive network.

In 2018, EMODnet also contributed to developing inclusive and open stakeholder engagement across the European ocean observing and data management communities. This culminated in the first EOOS Conference (Larkin et al., 2019), specifically aimed to connect diverse and disparate communities across Europe. Funded by the European Commission and co-organized by EMODnet, the European Marine Board and EuroGOOS, the Conference brought together about 300 stakeholders from the ocean observing, monitoring, and data management communities and users, spanning public and private sectors and from research to monitoring for public authorities and for the blue economy.

EMODnet IN THE NEXT DECADE

In its third development phase (2017–2020), EMODnet is now sufficiently mature to provide considerable value for industry and the public sector. Despite this, there remains an opportunity for EMODnet to further mobilize new users to fully exploit this immense resource. Two areas in particular provide scope for further improvement: users beyond Europe and business users. Additional opportunities lie in aligning and, where possible, integrating with other European data and information sharing initiatives. EMODnet is already actively engaged in developing synergies with the European Atlas of the Seas (EAS), frameworks such as the European Ocean Observing System (EOOS) and global initiatives such as the GEOSS geoportal, Together these activities and developments are expected to take EMODnet to a new dimension as one of the leading global actors in ocean observing, data management and information provision services for an expanding user base comprising the general public, professionals and data experts alike.

The EMODnet Secretariat's vision is to support the network by fostering a culture based on learning by doing, to listen to users and build on the strengths of each of the partners involved. Providing easy access to high quality, interoperable marine data, and products free of restrictions on use is clearly at the core of EMODnet. Nevertheless, EMODnet is more than a distributed data infrastructure. EMODnet provides a collaborative platform for them to advance work on standards, to develop synergies, reduce fragmentation, and create a cohesive community capable of solving problems that no single entity can address on their own. In the European context, EMODnet illustrates that by working together we can achieve results which would never be possible if countries were to act on their own.

[27] www.opensealab.eu

The Main Axis of the Strategic Vision for the Next Few Years

The key short-term objective for EMODnet partners is to deliver the vision target of a seamless multi-resolution digital seabed map of European waters by 2020, covering all EMODnet themes, easily accessible, interoperable, and free of restrictions on use. This objective will be accompanied by a process that helps European countries maximize the potential of their marine observation programmes via data adequacy assessment at sea-basin scale. As already suggested, the Checkpoint exercises could be undertaken periodically as part of this process.

The main challenges that will need to addressed by the EMODnet data portals in the third and final development phase (2017–2020) are to (1) further improve data coverage, quality, and resolution (more data, new parameters, new products, etc.); (2) improve coherence, harmonization and interoperability, within each thematic area, amongst the different EMODnet thematic data portals and with international initiatives/systems; (3) improve existing and develop new integrated central access data services to search, visualize and retrieve data resources from different thematic sub-portals simultaneously; (4) improve accessibility of the available data, products, and services via remote machine-to-machine connections and provide adequate documentation; (5) further improve the visibility of the resources, in particular by intermediate users from the public and private sector to create value and by global users to support international ocean governance processes, amongst others; (6) demonstrate successes; and (7) strengthen the user/service-orientation.

EMODnet for Global Users

Whilst the focus of development within EMODnet and its thematic groups has been to support activities and the development of products at the European scale, this activity cannot take place in isolation. More than half of the 17 United Nations Sustainable Development Goals are related to the marine environment and the challenges of global data interoperability lie at the heart of ensuring a comprehensive evidence base is assembled to help achieve these goals. In addition, by 2030 the ocean economy is predicted to have a value in excess of three trillion US dollars (OECD, 2016). The need to balance the negative impacts on biodiversity and ecosystem services with sustainable growth and increasing demands has never been greater.

Without the development of inclusive, open standards and practices the capability to respond to these challenges is greatly diminished. Development must include the parallel provision of training, tools and services to lower the barriers to data uptake for a truly global audience to participate. Global networks are able to reach a wide community and ensure promotion and access to standards. However, without regional integration the ability to deliver meaningful, informative, and high-utility products is greatly reduced. Most EMODnet thematic assembly groups are providing these products and services at the European level while actively working with the global community to ensure the highest degree of integration and interoperability.

Since 2016, DG MARE has been developing an EMODnet internationalization strategy with the objective to make EMODnet more visible and relevant for international users/stakeholders and to strengthen interoperability with global data systems and initiatives. This is done among others via the creation of EMODnet dedicated community sections on the central portal, by feeding data products to global repositories (e.g., Ocean Data Portal and GEOSS geoportal), and by ingesting/providing data from areas beyond European waters. As part of these efforts, EMODnet partners will continue to connect and participate in projects with an international scope (e.g., EU funded projects such as ATLAS[28], AtlantOS[29], ODIP[30], and EuroGEOSS[31], ...), contribute to setting standards at European and international level, and establish and share best practices (e.g., via the IOC-UNESCO ocean best practices repository).

Future User Orientation and Stakeholder Engagement

The transition to more user-oriented developments underpinned by stakeholder engagement is a priority for EMODnet to become a fully user-driven service. This will require much greater interaction with users and stakeholders. To achieve this, the EMODnet portals will move beyond data provision, to become also a facility for engagement and communication with both data providers and users. Dedicated services such as community portals for specific projects or initiatives, in return for data or other contributions already exist (e.g., EMODnet Physics for AtlantOS, JERICO-NEXT, SOOSmap, and others) and should be further explored. Providing a dashboard function with statistics on usage and information to data providers is another way to strengthen links with core stakeholders and secure the integrity in the long term (already available for EMODnet Physics). In order to better understand user needs, EMODnet will continue to actively seek feedback and collect information about usage via online surveys, helpdesk functions, feedback forms, download forms, and targeted user assessments.

Specific emphasis will continue to be placed on making EMODnet more known and used by businesses, both as provider and user. In particular, SME's, consultancies and intermediate users will be a key target, as they can be considered to be the catalyzers of value creation along the marine knowledge value chain.

Strengthen Connectivity Between Different Components of the Marine Knowledge Value Chain

The marine knowledge value chain can be considered to cover the progression of data from their collection to their use, with value being created at various stages, from the acquisition of metadata

[28] https://www.eu-atlas.org/

[29] The idea for EMODnet Atlantic pages originated from work done in the framework of the AtlantOS project on how marine data portals can better support and engage with stakeholders relying on ocean observing and data across the Atlantic http://www.emodnet.eu/atlantic-1

[30] http://www.odip.eu/

[31] https://www.earthobservations.org/activity.php?id=145

on collection, to processing the data into information products that can ultimately be used for decision making or economic value creation. Up until 2017, EMODnet had focused mainly on data assembly, harmonization, and sharing. To fully realize the potential of the now mature and operational EMODnet, there is a need to expand the focus and scope of activities along the entire marine knowledge value chain, from merely data sharing toward (1) more upstream (data collection) by improving the data ingestion process and aligning with the emerging EOOS; and (2) more downstream by making EMODnet data products and information outputs more relevant and accessible to a wider public, via sharing tools such as the European Atlas of the Seas (EAS), which, since 2017, is being further developed by the EMODnet Secretariat. The strengthening of these interlinkages will hopefully contribute to a structuring process leading to a coherent EOOS, well-aligned with EMODnet and value-added information service providers, with the scale and visibility to create an ocean business market/ecosystem around data collection, management/sharing and the generation of information services for end-users.

In addition, with the upcoming United Nations Decade on Ocean Science for Sustainable Development and the wider UN 2030 agenda and Sustainable Development Goals (SDGs) EMODnet will accelerate its efforts to make its services providing data and data products more interoperable with wider European, regional, and International data initiatives. This will include applying, where relevant, ocean best practices such as semantic ontology to ensure data and data products are also more discoverable to a wider user community and searchable according to their relevance to SDGs.

Sustainability of EMODnet

EMODnet does not operate *in situ* observing platforms but assembles observations in cooperation and coordination with existing programmes and projects (the data initiatives, mentioned in **Table 2**). As already explained, these data initiatives are supported and maintained with major input from national stakeholders. These stakeholders are research and governmental organizations that are involved in marine data collection and data management, running data centers (data originators and data assembly centers). This implies that the upstream pillars of EMODnet are well-funded, supported by long-term initiatives and operations within national strategies related to the marine environment. By building upon these existing initiatives and developing beneficial partnerships, EMODnet has ensured an optimization of resources.

On the downstream part, EMODnet has made huge progress, not only in unlocking and facilitating access to data, but also in developing added-value services and products for varied user communities. There are many examples that show EMODnet impact like, for instance, the EMODnet Bathymetry digital terrain model (DTM) of the European seas. This DTM (resolution of 1/16 * 1/16 arc min, i.e., grid of 115 m resolution) is the best on the market and finds its way to many numerical modelers for tide and wave forecasting, offshore industry such as oil and gas companies, wind farm operators, dredging companies, pipeline engineering companies, coastal protection managers, and many others. Another good example is EMODnet Chemistry that brings together a large number of chemical data on eutrophication and contaminants that serve the MSFD process. This has led to the decision by EEA to accept EMODnet as an important source of data for supporting the MSFD process and advising Member States to make use of EMODnet for reporting as one of the preferred options. Likewise, the recent Horizon 2020 Work Programme H2020-2018-2020 for "Food security, sustainable agriculture and forestry, marine, maritime and inland water research and the bioeconomy" reads that "*Data collected shall be in line with agreed standards, be openly available via portals (including EMODnet).*" DG MARE is also building agreements for cooperation with other European initiatives such as Copernicus, the DCF the MSP Directive, and the MSFD, for greater synergy and integration with a clear goal toward long-term integration. In summary, EMODnet's crucial role in continuing to support and contribute to these important policy objectives, as well as to Europe's blue economy, guarantees its sustainability into the future.

While the political commitment clearly exists to maintain EMODnet as a long-term permanent service, the exact scope, governance, and mechanism of funding beyond 2020 have yet to be fully defined. The Marine Knowledge 2020 Strategy mapped out the evolution of EMODnet until 2020. Now is the time to plan for the post 2020 EMODnet era. In November 2019, all EMODnet partner organizations and stakeholders will gather to consider the future roadmap of EMODnet on the longer term. It is expected that the aforementioned priorities of the final development phase (leading up to 2020) will also drive how EMODnet evolves beyond 2020.

CONCLUSIONS

EMODnet originated from the need to unlock the potential of fragmented and hidden marine observations and data stored in a myriad of data systems and repositories scattered all over Europe. This was critical because the data collected through observations can only generate knowledge and innovation if Europe's engineers and scientists are able to find, access, assemble and apply them, efficiently and rapidly. Since its creation in 2009, EMODnet has greatly alleviated this problem by providing access to a broad range of harmonized marine observations/data and data products across seven thematic domains.

User feedback indicates that there is a general sense of appreciation for the work done by the thematic assembly groups, in particular to collate and harmonize the often disperse and fragmented data resources. With a growing range of data services and steady improvements of data products of broad interest, EMODnet shows what can be achieved if we work together beyond national borders. It is a true success story of European collaboration.

However, EMODnet has done much more than providing access to data, metadata, and products. It has created a network and community of experts and specialists working to promote the development and adoption of standards, sharing best practices, and technical solutions to promote integration and interoperability between various systems. Through a series of data stress-tests, the EMODnet Checkpoints have helped with the identification of important data gaps or issues in data collection or sharing that, if left unchecked, inhibit our ability to address important societal questions. But perhaps its greatest added value is that EMODnet acts as a platform for collaboration, bringing together key European ocean observation/data providers, integrators, networks, and infrastructures (EuroGOOS ROOS, CMEMS, SeaDataNet, OBIS, ICES, PANGAEA, Regional Sea Conventions, hydrographic offices, geological surveys, etc.). As such it has greatly contributed to reducing fragmentation and increasing efficiency in the European marine data landscape, as well as in instigating a coordinated, interoperable data sharing framework. EMODnet has also been instrumental in nourishing and advancing the developing culture of open data sharing, in the public sector, academia and the maritime industry, both in Europe and beyond.

In order for data providers and users to invest time in both using and contributing to any data provision service, they have to trust in the reliability of the service. As a long-term EU data initiative supported by the European Commission, EMODnet has gained this trust amongst many providers and users. To build on this, EMODnet is continuously evolving, improving the tools available and widening thematic and geographic coverage. It is uniquely multidisciplinary, pan-European and increasingly global in scope and coverage, largely as a result of the internationalization strategy. Making EMODnet services, data and products more relevant and available to international users and data sharing facilities (e.g., GEOSS geoportal) will therefore become even more important in the future than it has been until now.

With the promotion efforts of the EMODnet Secretariat and the creation of a central access portal, the number of satisfied users has steadily grown over the years. As such, EMODnet has greatly increased the visibility, potential and re-use of Europe's wealth of marine observations, and data resources.

While EMODnet will maintain its core function of providing access to marine data, metadata, products, and services, it will also continue to grow and further strengthen engagement with stakeholders, users, and other initiatives, to create new off-shoots all along the marine knowledge value chain, at European and global level.

AUTHOR CONTRIBUTIONS

BM is the lead author, coordinated the drafting and wrote the part describing EMODnet Checkpoints. AN, MV, and SC are the lead authors of the in-depth sections describing Physics, Chemistry, and Biology portal, respectively. AG, NA, TS, and AP are coordinators of the rest of EMODnet portals. QH, NP, BK, JP, JS, and AVP are coordinators of the EMODnet Checkpoints. SI is the coordinator of the Data Ingestion project together with DS, who wrote the corresponding text and provided input to Chemistry section as well as during the review process. J-BC wrote the forward-looking final part and conclusions. OM and PO wrote parts providing the background and describing the Central Portal, respectively. Other co-authors writing text were DL, GM, PG, and KL. AP, OM, NA, and NH also revised the text. SS assisted with the editing and formatting. The rest of the co-authors work actively in different strands of EMODnet and provided other types of inputs such as Figures and Tables or further comments.

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REFERENCES

Buck, J. J. H., Bainbridge, S. J., Burger, E. F., Kraberg, A. C., Casari, M., Casey, K. S., et al. (2019). Ocean data product integration through innovation-the next level of data interoperability. *Front. Mar. Sci.* 6:32. doi: 10.3389/fmars.2019.00032

Busalacchi, A. J. (2009). "Celebrating a decade of progress and preparing for the future: ocean information for research and applications," in *Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society,* Vol. 2, eds J. Hall, D. E. Harrison, and D. Stammer (Venice :ESA Publication WPP-306).

Calewaert, J. B., Weaver, P., Gunn, V., Gorringe, P., and Novellino, A. (2016). "The European Marine Data and Observation Network (EMODnet): your gateway to european marine and coastal data," in: *Quantitative Monitoring of the Underwater Environment. Ocean Engineering & Oceanography,* Vol 6, eds B. Zerr, L. Jaulin, V. Creuze, N. Debese, I. Quidu, B. Clement, A. Billon-Coat (Cham: Springer), 31–46.

EEA Report No 2/2015 (2015). *State of Europe's Seas*. Available online at: http://www.eea.europa.eu/media/publications/state-of-europes-seas

European Commission (2010). *Marine Knowledge 2020 Marine Data and Observation for Smart and Sustainable Growth*. Commission Communication COM(2010) 461, Publications Office of the European Union.

European Commission (2012). *Marine Knowledge 2020 from Seabed Mapping to Ocean Forecasting*. Green Paper, Publications Office of the European Union, Luxembourg. Available online at: https://ec.europa.eu/maritimeaffairs/sites/maritimeaffairs/files/docs/body/marine-knowledge-2020-green-paper_en.pdf

European Union (2007). Directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007 Establishing an Infrastructure for

Spatial Information in the European Community (INSPIRE). Available online at: http://data.europa.eu/eli/dir/2007/2/oj

European Union (2008). Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 Establishing a Framework for Community Action in the Field of Marine Environmental Policy (Marine Strategy Framework Directive). Available online at: https://eur-lex.europa.eu/eli/dir/2008/56/oj

Fischer, A. S., Hall, J., Harrison, D. E., Stammer, D., and Benveniste, J. (2010). "Conference summary-ocean information for society: sustaining the benefits, realizing the potential," in *Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society,* Vol. 1, eds J. Hall, D. E. Harrison, and D. Stammer (Venice: ESA Publication WPP-306). doi: 10.5270/OceanObs09.Summary

Larkin, K., Marsan, A.-A., Tonné, N., and Calewaert, J.-B. (eds) (2019). *EOOS Conference 2018 Report and Call to Action. Connecting European Ocean Observing Communities for End-to-End Solutions.* Brussels: The Egg, 21–23.

OECD (2016). *The Ocean Economy in 2030*. Paris: OECD Publishing. Available online at: http://dx.doi.org/10.1787/9789264251724-en

Pearlman, J., Bushnell, M., Coppola, L., Karstensen, J., Buttigieg, P. L., Pearlman, F., et al. (2019). Evolving and sustaining ocean best practices and standards for the next decade. *Front. Mar. Sci.* 6:277. doi: 10.3389/fmars.2019.0027

Pinardi, N., Manzella, G., Simoncelli, S., Clementi, E., Moussat, E., Quimbert, E., et al. (2017). "Stress testing the EU monitoring capacity for the Blue economy. Operational oceanography serving sustainable marine development," in *Proceedings of the Eight EuroGOOS International Conference*, eds E. Buch, V. Fernández, D. Eparkhina, P. Gorringe and G. Nolan (Brussels, Bergen EuroGOOS) 3–5

Roarty, H., Cook, T., Hazard, L., Harlan, J., Cosoli, S., Wyatt, L., et al. (2019). The global high frequency radar network. *Front. Mar. Sci.* doi: 10.3389/fmars.2019.00164

Rubio, A., Mader, J., Corgnati, L., Mantovani, C., Griffa, A., Novellino, A., et al. (2017). HF radar activity in european coastal seas: next steps toward a pan-European HF radar network. *Front. Mar. Sci.* 4:8. doi: 10.3389/fmars.2017.00008

Shepherd, I. (2018). European efforts to make marine data more accessible. *Ethics Sci. Environ. Polit.* 18, 75–81. doi: 10.3354/esep00181

Troupin, C., Barth, A., Sirjacobs, D., Ouberdous, M., Brankart, J.-M., Brasseur, P., et al. (2012). Generation of analysis and consistent error fields using the Data Interpolating Variational Analysis (DIVA). *Ocean Model.* 52–53, 90–101. doi: 10.1016/j.ocemod.2012.05.002

Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J. J., Appleton, G., Axton, M., Baak, A., et al. (2016). The FAIR guiding principles for scientific data management and stewardship. *Sci. Data* 3:160018. doi: 10.1038/sdata.2016.18

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APPENDIX

Appendix A1 | Main identified gaps and suggested solutions by the Checkpoints, disclosed by parameter.

Parameter	GAP	Suggestion
AIR		
Wind	• Wind profiles observations above 10 m height (required for Wind farm siting challenge) are scarce and generally not public. • Wind data for applications at the coast do not have enough resolution (this is also the case for currents and waves).	• LiDAR could be an alternative for cost-effective monitoring, but it needs *in situ* wind profiles for calibration. • High Frequency Radars (HFR) can become a key tool for monitoring currents, waves, and winds near the coast. • Some Checkpoints used commercial solutions that provided fit-for-use data that enabled them to fulfill Wind farm siting challenge.
SEAWATER—PHYSICS		
Ocean currents	• Horizontal resolution of publicly available current data (models) is not enough for Wind farm siting and Oil spill challenges. More observational data would be desirable. Horizontal coverage is also an issue for the Atlantic Checkpoint.	• As for wind data, HFR can be an alternative. • Improved resolution models nested in CMEMS should be developed for the near-coastal areas.
Waves	• Public wave data (models) do not have enough horizontal resolution for Wind farm siting and Oil spill. Wave data are also important to study sediment transport at the coast. Again, resolution is too coarse for this kind of studies.	• Same as above
Sea level	• The number of sea level stations providing long-enough time is insufficient and there should be more GPS-colocated tide gauges to fulfill the Coasts challenge (all but Baltic).	• Tide gauges should be maintained in time and new stations equipped with GPS could be added (but this is very expensive). Baltic Sea Checkpoint combined *in situ* and model reanalysis data to successfully undertake the Coasts challenge.
Sea ice	• Sea ice coverage is less of an issue than sea ice thickness, in particular for the Climate challenge (for Wind farm siting purposes it seems enough, because there are recent data).	• Satellite data and models could be an alternative.
SEAWATER—CHEMISTRY		
Nutrients (nitrogen, phosphates)	• The coverage and resolution are not enough (except in the Baltic Sea), in particular at the coastal zone, and this hinders achieving the challenge in eutrophication.	• Increase monitoring but, above all, ease access to existing datasets whose access is often restricted (moratorium).
Chlorophyll-a	• Same as above	• Same as above
Dissolved oxygen	• Same as above	• Same as above
SEAWATER—BIOLOGY		
Phytoplankton	• Visibility and accessibility of the datasets is good, but the coverage is not enough to fulfill the challenges (MPA, Climate).	• More monitoring is needed
Reptiles, Sea mammal, Birds counts, Birds migration routes	• These data are needed in several challenges (Wind farm siting, MPA) and in general there is a lack of coverage but also when available, data are too scattered, and difficult to aggregate.	• More monitoring and harmonization of analysis protocols and descriptions.
Alien species	• Same as above: lack of data and too much heterogeneity in the sampling protocols.	• Same as above
MATRIX FRESH WATER		
Water discharge	• Availability of river discharge data has recently improved thanks to EMODnet Physics, but at the moment of undertaking the River challenge, most Checkpoints (except Black Sea) identified a lack of coverage and resolution.	• Rivers should be monitored regularly, standards for monitoring best practices to be established.
Sediment load	• There is a clear gap for this parameter, which is very relevant for Coastal and River Input Challenges. Except for the Black Sea, there are not enough observational data.	• More rivers should be monitored regularly. • Satellite data (Mediterranean) and models (Baltic) are offered as complementary to improve sediment mass balance estimation in the absence of data.

(Continued)

Appendix A1 | Continued

Parameter	GAP	Suggestion
Nutrients (nitrogen, phosphates)	• Very few observations, scattered, low coverage, and resolution.	• More river inputs should be monitored regularly. • Models could be useful to simulate temperature (Baltic) but would nevertheless require more observations for validation.
Eels/Salmon	• These variables proved not too relevant for some of the sea-basins (Black Sea, and Arctic). They were sufficient for the smaller basins (North Sea and Baltic), but insufficient in Atlantic and Mediterranean.	• More rivers should be monitored regularly for fish-abundance.
River temperature	• Same comment than for Nutrients in rivers	• Same comment than for Nutrients in rivers
BATHYMETRY		
Bathymetry and Elevation	• For many of the challenges, aggregated datasets like EMODnet bathymetry are enough. This is the case for Wind farm siting (in some areas), MPAs or Oil platform leak. However, for other challenges that require higher resolution, especially at the coast, less data are available, and they are normally accessible with restrictions (costs, delays) that are country dependent.	• Obviously, a solution to improve resolution would be to increase the sampling, but this is extremely costly. Better metadata would in any case be advisable in order to select the right type of dataset and decide whether it is preferable to opt for a commercial solution in order to save processing time. • Encouraging lower fees for bathymetric datasets that are within Hydrographic offices would also be desirable.
SEABED/RIVERBED		
Lithology	• Much greater resolution would be needed to address challenges like Wind farm siting.	• More surveys
Sediment balance data	• Data on sediment is clearly insufficient to obtain a basin-scale view of shoreline advance or retreat all over European coasts, and this is highlighted as a priority by the Mediterranean Checkpoint.	• More *in situ* monitoring and/or combination with satellite monitoring and modeling, monitoring best practices to be established.
Habitat extent and characteristics	• Needed for MPA, Oil spill impact forecasting, and to assess impact of Fisheries on the seabed. In general, their availability and resolution are considered insufficient (with the exception of the UK that has a Marine register database).	• Increase efforts both in new surveys but also in creating aggregated datasets.
HUMAN ACTIVITIES		
Pipelines and cables, Military activities areas, Aquaculture sites, Industrial activities, Leisure activities, Scientific activities…	• Data on human activities were needed for several of the challenges (Wind farm siting, Marine Protected Areas, Oil Platform Leaks). Even though the visibility through EMODnet Human Activities is good, responsiveness is not always fast enough. Also, there are a number of gaps (countries that do not provide data), depending on the variable.	• This seems clearly more a question of improving the accessibility than of increased monitoring.
Maritime traffic data	• Vessels tracking data deemed necessary for many challenges (Wind farm siting, MPA, Oil spill, Fisheries Impact, and Alien Species) but they were not downloadable.	• Another case where the problem lies in the accessibility of the data, and not in a gap in monitoring. EMODnet Human Activities has contributed to fill in this gap with the release of a Vessel Density Map in March 2019.
Fisheries catches/landings	• The Data Collection Framework (DCF) obliges the EU Member States to collect this type of data, which are managed by the Joint Research Council (JRC) for scientific purposes. However, with the exception of the Black Sea, most of the Checkpoints detected deficiencies: data were not obtained easily or did not have the right format.	• Access to data on catches and landings from DCF should improve. • ICES can be an alternative source of data.
Fisheries bycatch and discards	• Data on discards (especially discards in numbers vs. discards in mass) are very scarce and only exist for certain species. When they exist, their quality is doubtful. All Checkpoints (except the Black Sea) coincided in highlighting this problem. Bycatch data are even more difficult to find, in particular for mammals and birds.	• More monitoring could become part of the DCF to obtain data on discards and bycatch. In the Baltic Sea, bycatch data may improve once a suitable monitoring scheme is agreed upon at the Baltic Sea level.

frontiers in Marine Science

REVIEW
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Collaborative Science to Enhance Coastal Resilience and Adaptation

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Impacts from natural and anthropogenic coastal hazards are substantial and increasing significantly with climate change. Coasts and coastal communities are increasingly at risk. In addition to short-term events, long-term changes, including rising sea levels, increasing storm intensity, and consequent severe compound flooding events are degrading coastal ecosystems and threatening coastal dwellers. Consequently, people living near the coast require environmental intelligence in the form of reliable short-term and long-term predictions in order to anticipate, prepare for, adapt to, resist, and recover from hazards. Risk-informed decision making is crucial, but for the resulting information to be actionable, it must be effectively and promptly communicated to planners, decision makers and emergency managers in readily understood terms and formats. The information, critical to forecasts of extreme weather and flooding, as well as long-term projections of future risks, must involve synergistic interplay between observations and models. In addition to serving data for assimilation into models, the observations are also essential for objective validation of models via hind casts. Linked observing and modeling programs that involve stakeholder input and integrate engineering, environmental, and community vulnerability are needed to evaluate conditions prior to and following severe storm events, to update baselines, and to plan for future changes over the long term. In contrast to most deep-sea phenomena, coastal vulnerabilities are locally and regionally specific and prioritization of the most important observational data and model predictions must rely heavily on input from local and regional communities and decision makers. Innovative technologies and nature-based solutions are already helping to reduce vulnerability from coastal hazards in some localities but more focus on local circumstances, as opposed to global solutions, is needed. Agile and spatially distributed response capabilities will assist operational organizations in predicting, preparing for and mitigating potential community-wide disasters. This white paper outlines the rationale, synthesizes recent literature and summarizes some data-driven approaches to coastal resilience.

Keywords: coastal observations, numerical models, coastal flooding, big data, collaboration, community vulnerability, climate change, urban coasts

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INTRODUCTION AND GOALS OF THIS WHITE PAPER

As pointed out by Wright and Nichols (2019): "*A high priority vision for future coastal science should be to enhance resilience of coastal communities by anticipating and mitigating hazards to human health, safety and welfare and reducing economic harm to coastal industries such as tourism, fisheries and shipping.*" Accomplishing this objective will require anticipating future hazards to human and ecosystem health, safety and welfare. To adapt to accelerating coastal change, we must predict future conditions with increasing accuracy and precision, providing improved predictions on global, regional, and local spatial scales and on decadal, annual, and event time scales. Meeting future challenges requires collaborations across the broadest range of disciplines and coastal landscapes to integrate and assess observational data and model output. This will require a trans-institutional collaborative environment and active engagement with local communities and NGO's, especially those in resource poor regions. Effective prediction of conditions at a specific coastal site requires a hierarchy of coupled multi-disciplinary models in combination with spatially distributed observations to provide predictions downscaled from the global to the local level. Improved knowledge of natural and social processes and their interactions will result in the development of actionable information to reduce coastal vulnerability. Because of the diversity and complexity of coasts and coastal communities, observing and predicting strategies must be tailored to local circumstances and driven in large measure by input from local stakeholders and policy makers.

The primary goal of this white paper is to motivate development and outline the possible functions of a *virtual coastal environment* within which a cyber-connected network of stakeholders and scientists from different disciplines can interconnect and share needs, insights, observational data, model codes, model output, objective evaluations of models and forecasts and, ultimately, communicate results to diverse end users including local communities. Some specific objectives related to OceanObs'19 are to advocate for greatly expanded collaboration, outline some of needs for the future and offer a summary review of recent literature related to coastal resilience. Global collaborations must include academic, government, and industry colleagues supported by multi-agency investments and international partnerships. Local and regional collaborations must also involve community stakeholders and policy makers. To become an integral part of future operational systems, the virtual environment must rely on linked observation and modeling systems capable of meeting both existing and expected future critical needs for coastal resilience. We must address today's coastal problems within an integrated framework that complements existing operational systems and assists in identifying future modeling requirements. In this white paper, we offer a brief synthesis of some diverse perspectives and strategies recognizing that solutions to coastal threats must be found at local and regional levels. There is no "one size fits all" global model for coastal resilience.

OBSERVING AND PREDICTING TO ENABLE RESILIENCE

According to a National Academies report on disaster resilience (National Academies, 2012): "*Resilience is the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events.*" This point was reiterated in a more recent National Academies report on community resilience focused on the Gulf of Mexico coast (National Academies of Sciences, Engineering, and Medicine, 2019). Resilience involves the ability to adapt to changing environmental, economic, and social stressors. It does *not* imply constancy. It is the capacity to change and adapt while retaining effective viability. There are other definitions for coastal resilience, but we suggest one that focuses on enabling a community or environment to "bounce back" after a hazardous event such as a hurricane that causes flooding or to progressively adapt to long-term environmental changes in hazards and risks. In many cases, adaptation may involve adjusting infrastructure, relocating housing, or altering socio-economic behavior. Of paramount importance is the notion of *preparing for* natural hazards (Wright et al., 2016).

Numerous authors have described how physical, biological, and anthropogenic processes shape and impact the coast (Carter, 1988; Komar and McDougal, 1988; Paskoff, 1993, 1998; Camfield and Morang, 1996; Doornkamp, 1998; Bernatchez and Fraser, 2012; Ranasinghe and Jongejan, 2018). The European *Eurosion* project has shown that human influence, particularly urbanization, in the coastal zone has increasingly exacerbated coastal erosion (Salman et al., 2004). Some other examples are reviewed in a recent book on future coastal change (Wright and Nichols, 2019). The overall sensitivity of a coast to physical and biological forces determines the impacts of extreme conditions and human activities. The ability of a coast to adjust to different conditions is one component of resilience. The ensuing land-use planning considerations can increase or decrease the level of resilience depending on how well informed the decision makers are. Spatially distributed observations, on land and in the coastal ocean and nearshore are essential to adaptive coastal management. These observations need to account for the locally specific coastal dynamics and hazards as well as the different stakeholders, management and societal considerations. Rates of recovery of coastal realms following extreme events vary dramatically depending on local configuration and built infrastructure. Equilibrium responses to anthropogenic impacts can require several decades. Plans must take account of environmental factors, locally available resources, costs and benefits, and the most urgent needs of the local communities.

Risk depends on the combination of hazards, impacts, and vulnerabilities. A knowledge of impacts, such as coastal erosion and flooding, is needed at a range of time scales. This is especially important since the rates and demographics of coastal urbanization have shown significant temporal variability, and this has seriously challenged coastal management. Only through the integration of nearshore monitoring, modeling and adaptive management can plans be effectively implemented to increase resilience by relocating high-value assets and vulnerable people to less threatened areas or by redistributing resources needed for flood or erosion mitigation. The strategies required to resettle, or otherwise protect, threatened, or displaced communities and help them adapt to changed or new environments is a major challenge for governments, particularly in regions such as the Bay of Bengal (Wright, 2019).

To be effective and trusted, models and data must involve objective testing to ensure accuracy and coupling across multiple disciplines. An essential element of effective future coastal forecasting systems, in addition to observations and models, must be advanced data management, dissemination and visualization systems that enable modelers to readily access observational data for assimilation and objective model validation. Forecasting systems should provide planners, emergency managers, and the general public with clear and readily understandable information to assess impending threats. Some of this is now technically possible by rapidly evolving high-performance computing technology and the Internet of Things (IoT), which connects an ever-growing number of smart devices for real time monitoring and tracking of many physical events.

RATIONALE AND IDENTIFICATION OF THE NEED

Systemic vulnerability is a key multidimensional concept in developing strategies for long-term coastal management. Based on an interdisciplinary approach to risk, one may assess "the fragility of a system as a whole" (d'Ercole and Pigeon, 1999). Vulnerability characterizes a society (or individual) subject to risks related to situational factors (e.g., hazards) and structural factors determined by the socio-economic, cultural, functional, and institutional context of a place and time. As illustrated in **Figure 1**, systemic vulnerability generally has four major components (Meur-Férec, 2008; Hénaff and Philippe, 2014): hazards; stakeholder involvement (people and property exposed to hazards); management (public policies of prevention and crisis management, defense works, and infrastructure); and representation (Meur-Férec et al., 2003–2004; Meur-Férec and Morel, 2004; Meur-Férec, 2006). Coastal observatories that apply a systemic approach to evaluating and monitoring the four components of vulnerability will be able to provide stakeholders with additional tools and methodologies to adapt to coastal risks. Enhanced long-term nearshore observations of physical and social processes will improve societies' understanding of and adaptation to high-impact, low-frequency natural hazards and climate change.

Assessment of the reliability and accuracy of predictive models requires continuous objective monitoring of what is actually happening and how those "happenings" impact resilience. Models, sensor arrays, data management systems, communication protocols, and collaboration strategies should be considered together and not "stove piped" into isolated subsystems. Similarly, the large pool of local community resources, such as citizen science projects, should be fully utilized to ensure representation in model systems of areas that may lack the resources to collect the required baseline and event data. There is an immediate need for increased observations of processes during extreme storms when waves, flooding, sediment transport, and morphological changes are large. Citizen scientists, whether members of the general public or dedicated volunteers, can contribute essential data in data sparse regions.

Sensors and models alone do not address the underlying issue of damaging long-term changes and extreme events acting on coastal communities of varying vulnerabilities. The nature and severity of the vulnerabilities of coastal communities must be assessed before the risks can be evaluated. In this context, observing systems and complementary models provide essential tools for problem-solving. Fully integrated physical and social data sets will help operators to test and improve coastal process models that can be applied to improve resilience. However, research is needed to investigate the statistical issues in synthesizing environmental and social science data that are collected at various locations, frequencies, and accuracies.

PREDICTING SOCIO-ECONOMIC VULNERABILITIES AND INUNDATION THREATS TO URBAN COASTS

Vulnerability Assessments

Worldwide there are 23 *megacities* with populations of over 10 million people. Of these, 16 are in the coastal zone (Blackburn and Pelling, 2014; Pelling and Blackburn, 2014). Hallegatte et al. (2013) and Dawson (2017) describe the dire plight of the growing number of people living in flood prone coastal cities and urban slums. Wright (2019) reviews recent literature on societal factors and changes that can impact community resilience including income, age and health, minority status, housing, and psychology. Some examples include works by Gunderson and Holling (2002), Norris et al. (2008), Cutter et al. (2010, 2014), and Van Zandt et al. (2012) who have evolved the concept of *Baseline Resilience Indicators for Communities* as empirical metrics for gaging the resilience of communities to disasters. Guillard-Gonçalves et al. (2014) developed a regionally specific "Social Vulnerability Index." Flanagan et al. (2011) developed a social vulnerability index for disaster management that considers 15 different factors obtained from census data. Existing cyber tools for quickly assessing the social vulnerability of coastal urban communities to rising water levels are the "Surging Seas" risk zone maps produced by *Climate Central*. **Figure 2** shows an example for New York City, NY, and Newark, NJ. Comprehensive, distributed data on elevations are crucial to accurate assessments of inundation probabilities associated with rising sea levels as well as event-scale storm surges and compound flooding (Gesch, 2018). It must be pointed out that the most vulnerable communities are not in affluent Western nations but in developing countries that have limited resources to protect or recover from disasters. Within the near future as many as 2 billion people worldwide could be in dire jeopardy. A very urgent

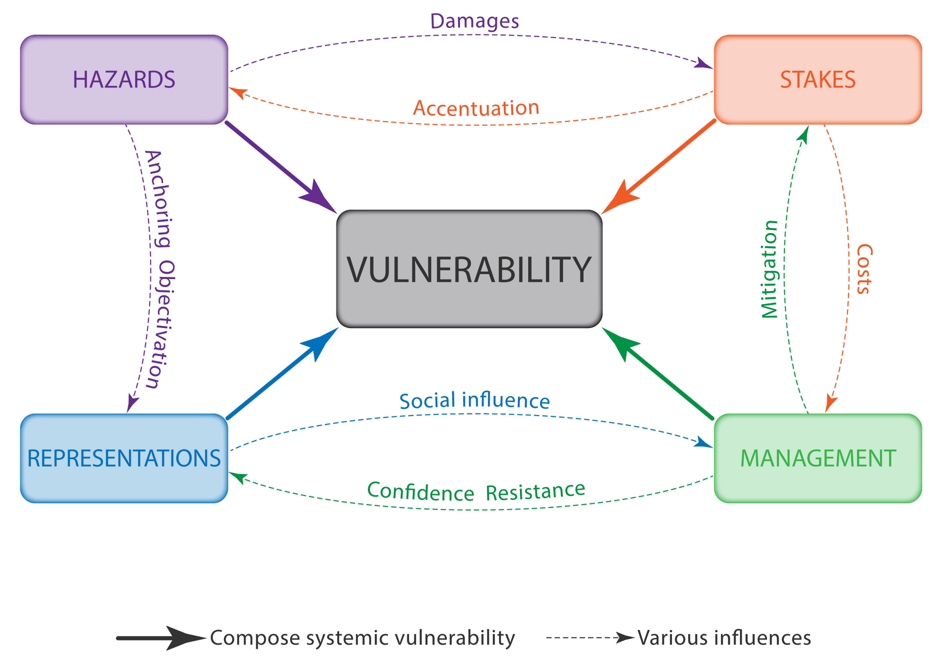

FIGURE 1 | Factors contributing to and interacting with vulnerability (Michel-Guillou and Meur-Férec, 2017).

challenge for international scientific organizations to find ways to make necessary observing, modeling and data dissemination technologies accessible to severely impoverished and threatened communities such as those that surround the Bay of Bengal (e.g., India, Bangladesh, Myanmar).

For the specific case of the United States, The US Army Corps of Engineers (USACE), Engineer Research and Development Center (ERDC) offers a tiered set of coastal resilience metrics that integrate engineering, environmental, and community resilience (Rosati et al., 2015). This approach factors parameters such as need, time, space, and available funding. Some cyber tools and websites that support decision making and emergency response at local and regional levels include the National Oceanic and Atmospheric Administration (NOAA) *U.S. Climate Resilience Toolkit*.[1] The local approaches advocated in the toolkit involve: (1) identifying the local climate related threats; (2) assessing risks and vulnerabilities; (3) exploring options; and (4) prioritizing actions allowed by available resources. The online toolkits for addressing vulnerabilities include the following interactive sites:

- Climate Change Vulnerability Assessment Tool for Coastal Habitats (CCVATCH)
- Coastal County Snapshots
- Coastal Flood Exposure Mapper
- Coastal Change Hazards Portal
- FEMA Flood Map Service Center
- Sea Level Rise and Coastal Flooding Impacts Viewer
- Surging Seas—Sea Level Rise Analysis by Climate Central

Next Generation Coastal Data Acquisition

Ocean observing systems provide environmental intelligence to a variety of users including weather forecasters, commercial and recreational mariners, emergency responders, coastal zone managers, researchers, educators, and more. Fully integrated observing systems consist of platforms, sensors, and technologies to transmit the data to users. Networks operated by NOAA range in size from PORTS®(Physical Oceanographic Real-Time System) to the U.S. IOOS®(Integrated Ocean Observing System) to the NDBC (National Data Buoy Center). Innovative new sensors may be integrated into ocean observing systems to improve our understanding of oceanographic phenomena. Affordable and miniaturized new sensors offer wider and more densely distributed portrayals of coastal processes and hazards at temporal and spatial scales that support decision making. Sensors, particularly water level sensors, widely distributed on land and along streets and highways provide real-time maps of spatially varying water levels during inundation events (Gesch, 2018).

Examples of new *in situ* sensor-based approaches to quantifying the problems of coastal flooding is offered by the Virginia *StormSense* Program and the Sea Level Rise Report Card site[2] maintained by the Virginia Institute of Marine Science of the College of William & Mary. Storm Sense, involves propagation of cost-effective water level sensors powered through the IoT, and has expanded the available offerings of ingestible data streams at the disposal of today's cities. *StormSense* is an IoT-enabled inundation forecasting research initiative working to

[1] https://toolkit.climate.gov

[2] http://www.vims.edu/research/products/slrc/compare/east_coast/index.php

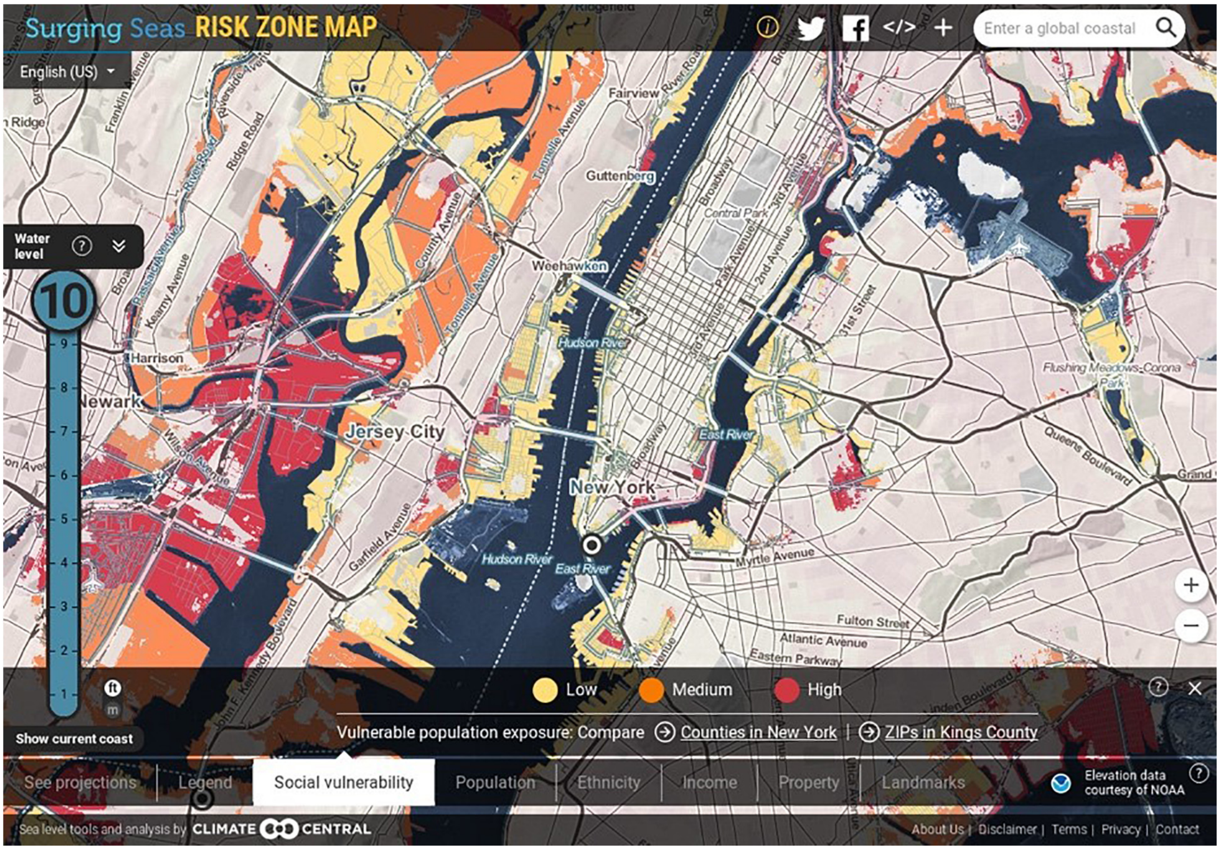

FIGURE 2 | Predicted social vulnerability of communities centered around New York City and Newark, New Jersey to a 10-foot storm surge or sea level rise. From "Surging Seas" risk zone maps produced by *Climate Central*. Orange, medium vulnerability; red, high vulnerability. Note the high level of vulnerability of several New Jersey communities.

enhance flood preparedness for flooding resulting from storm surge, rain, and tides. In this study, the results from 28 new water level sensors installed in summer 2017 helped establish the regional resilience monitoring network as recommended by Virginia's Intergovernmental Pilot Project. To accomplish this, the VA Commonwealth Center for Recurrent Flooding Resiliency's automated Tidewatch tidal forecast system (36-h lead time) is being used as a starting point to integrate the extant (NOAA) and new (USGS and *StormSense*) water level observing sensors throughout the Hampton Roads region of Virginia. The *StormSense* network employs ultrasonic and radar remote sensing technologies alongside web cameras with flood-edge detection capabilities. These new sensors recorded high water levels during Hurricanes Jose and Maria, and the November king tide in 2017. Observations from these events were used validate the inundation predictions of a street-level hydrodynamic inundation model. By the end of 2019, *StormSense* intends to automate flood control gates, communicate risk via chat-bots, and guide traffic patterns via route guidance apps to keep citizens out of the flood path.

The marine science community is making a great effort to address the estimation of parameters over large areas through *in situ* sensors, remote sensing, and numerical modeling. Instrumentation for recording atmospheric and oceanographic processes is continually evolving and, in many cases, becoming less expensive allowing for more widespread distribution of monitoring resources. Regional coastal observations within United States waters are currently supported by the U.S. IOOS, under the auspices of NOAA. Included under IOOS are arrays of *in situ* environmental sensors as well as the U.S. National High Frequency Radar Network. Radar is especially useful to extract both current and waves and supports operations such as search and rescue and oil spill cleanup. Although improvements in the spatial and temporal resolution of data for coastal applications are still needed, new generations of satellite and lower altitude remote observing systems are permitting high-resolution images to be obtained around the clock (Cazenave et al., 2017).

The French OSIRISC (Vers un Observatoire Intégré des Risques côtiers d'érosion-submersion) project (Hénaff, 2017; Marcel et al., 2018; **Figure 3**), involves the monitoring of coastal systemic vulnerability to erosion and flooding risks within an integrated observatory based on relatively simple and inexpensive data acquisition devices. A key element is the collection of data with relevant spatial representativeness and temporal frequency according to the processes being monitored. These simple indicators allow managers and citizens to participate in the data acquisition process. For example, erosion distance in the hazard component has been determined through spatially registered and oriented photography relying on landscape landmarks and the use of a measuring tape, high technology instruments using a laser pointer device for distance and angle measurements, or tachometer, differential GPS, photogrammetry, and laser scanners.

Remote sensing technologies provide increasingly accessible information for integrated coastal resilience. Recent advances in airborne and satellite-based radar and laser altimeters have the ability to map coastal topography and its changes at high spatial and temporal resolutions (Salisbury et al., 2017). Drones with high technology sensors are used to map the coastal zone following extreme weather. Guillot et al. (2018) describe flight plans and photogrammetric techniques that were used to study recovery of True Vert beach along the Gironde coast in France from severe storms during winter 2013/2014. Kovacs et al. (2018) have compared several multispectral satellites to classify submerged aquatic vegetation (SAV) in Moreton Bay located along the east coast of Queensland, Australia. This research is important since resilience indicators include the extent of SAV beds and the distribution of juvenile fish that depend on the SAV beds. Engineering and emergency managers may use different types of imagery to characterize the resilience of a built-up areas. Parente and Pepe (2018) describe the retrieval of bathymetry in turbid water near the port city of Lisbon by using radiometric band ratios from WorldView-3 imagery. Electro-optical and Synthetic Aperture Radar are important resources to provide updated maritime domain awareness near ports and harbors. Bannister and Neyland (2015) described the benefit of using regularly updated satellite images to improve maritime operations such as search and rescue. Scientists and engineers apply techniques such as change detection analysis with time series of images to characterize the environment to support planning. Bachmann et al. (2019) illustrated the use of hyperspectral imagery to improve coastal characterization and these approaches provide ocean observing systems with nearshore Digital Elevation Models and features from the land such as biomass and the water such as turbidity.

Bathymetric retrievals from hyperspectral imagery could be used to provide updated information for assimilation into nearshore models before, during, and after storms. Radar imagery continues to be an essential tool to mapping the changing polar regions in support of national ice centers, icebreaking, and those involved in climate studies. Community planners and resource managers are also using lidar data to fill critical information gaps as they devise plans to cope with rising seas, increased coastal flooding, and storm surges. Marine scientists, engineers, coastal zone managers, and other practitioners will increasingly depend on imagery to monitor critical facilities, the response of ecosystems such as a marsh or submerged aquatic vegetation beds to sea level rise, and to plan for resilient coastal communities.

Storm and flood waters are not the only issues of concern. Pathogens and toxins may adversely impact human health and ecosystems and require improvements in their measurement and modeling. Included are Harmful Algal Blooms, across a range of temporal and spatial scales. Some technological advancements have been made since the Fukushima Daiichi nuclear disaster that followed the Tōhoku earthquake on March 11, 2011. Effective ocean observing systems will need to exploit leading-edge sensor technologies for the detection of harmful substances and organisms in the ocean that range in size from radionuclides and microbes to bull sharks and ghost nets. Analytical tools including models may be applied to provide improved environmental information to emergency response, public health, and natural resource managers. Information may include potential threats to infrastructure such as power, sewerage and water, transport and communications systems. Observations and models are key to improving the mapping of dangerous marine organisms, chemical pollutants, or algal toxins that may help decision makers who must disseminate advisories or close shellfish beds or beaches to protect and prevent human illness. The resulting information archived by observing systems and models, needs innovative algorithms that improve contextual reasoning capabilities by recognizing anomalous situations and helping observing system users adapt to anomalies such as extreme weather. The development of Artificial Intelligence (AI) systems may provide tools for the large scale analysis of time series data (Shang et al., 2014). Coastal resilience including the provision of actionable information from AI will involve disparate data from thousands of data sets and computation of non-linear relationships between variables.

Marine scientists and engineers are developing new sensors that are deployable in networked monitoring systems to better observe changes occurring in coastal oceans (e.g., sea level rise, inundation, erosion, sea states, hypoxia, harmful algal blooms). For example, the planned France-based *Kineis* constellation of 20 nanosatellites will provide connectivity for ocean observing, fishing, maritime security, and more. The Partnership for Observation of the Global Oceans continues to contribute to sensor advances as evidenced by the expanding network of Argo floats that gather temperature, salinity, oxygen, and current velocity data. Important innovations are in development to improve the monitoring of carbon storage and biogeochemical processes, including the development of sensors to measure seawater carbon content, acidity, the concentration of nutrients such as nitrates and phosphorous and even genomic data.

Next Generation Numerical Models

The synthesis of ocean observations combined with accurate models is essential to addressing ecologic, economic, and community resilience. Coastal systems, structures, people and loss of habitat cannot be quantified without a combination of both of these tools. The breadth of scales in the dynamics of coastal processes makes it essential that both observational and modeling capabilities be improved and tightly linked. Today's numerical models for air-sea interaction, coastal circulation, waves and surges affecting the coast are adequate for many operational applications. However, the essential model tuning often relies on very sparse sets of objective measurements, particularly during extreme events. Improved validation is critically needed to improve model performance in coastal areas worldwide. Predictions and observations of coastal risk in relation to climate change are the subjects a recent

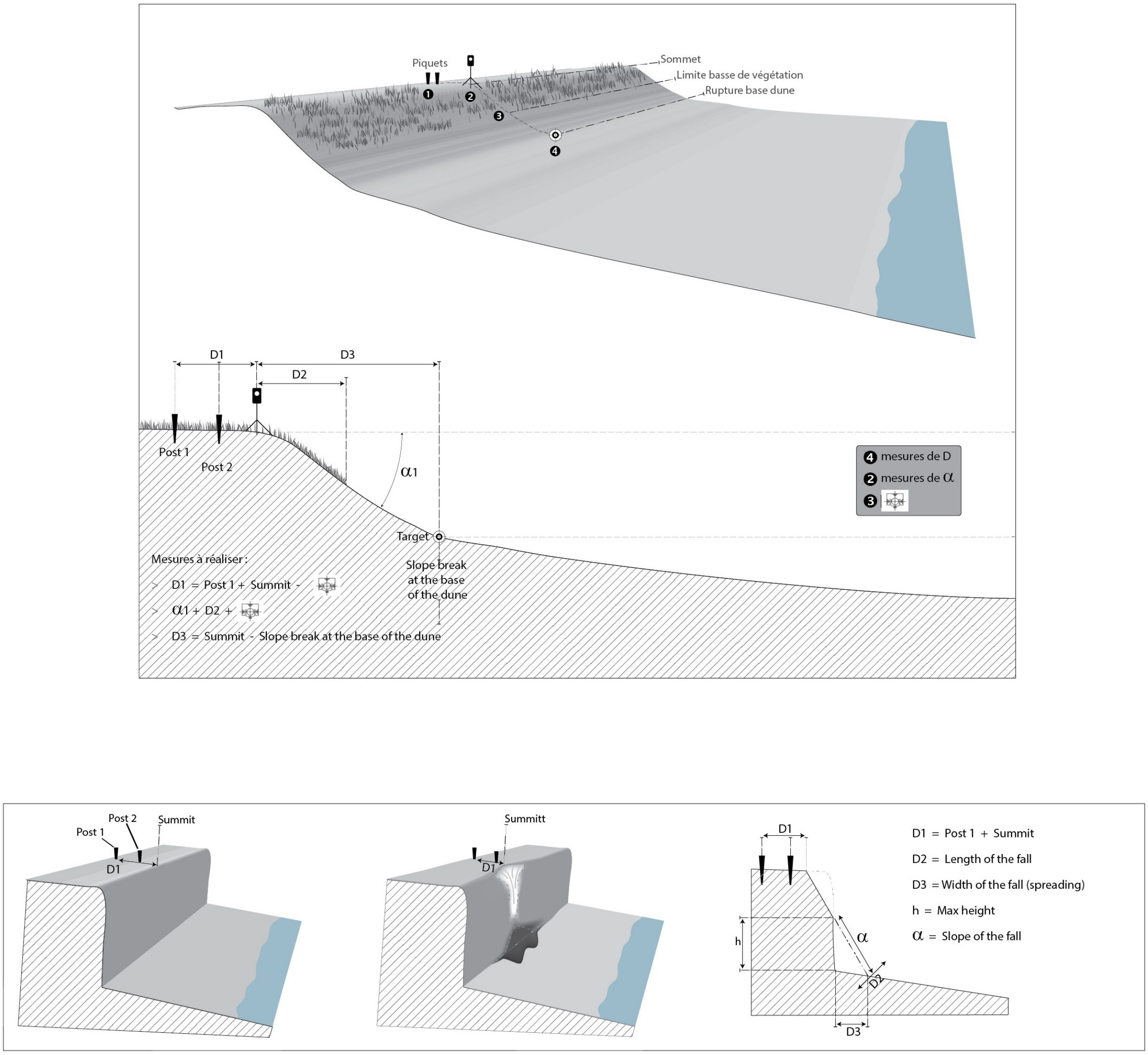

FIGURE 3 | Example of measurements carried out in the OSIRISC project (Hénaff, 2017; Marcel et al., 2018).

special issue of the *Journal of Marine Science and Engineering* (Ranasinghe and Jongejan, 2018).

The probability of severe storm surge and pluvial flooding jointly occurring in United States coastal cities has increased significantly over the past century (Wahl et al., 2015). In cases where rivers are nearby, fluvial flooding further exacerbates the severity of inundation. Reed et al. (2015) conclude that the risk of compound flooding in New York City is increasing. Urban coasts commonly include large low-lying and flood-prone areas often occupied by low-income and vulnerable residents. The most recent example of compound flooding of low-lying coastal towns was hurricane Florence which made landfall on the United States coasts of the Carolinas in September 2018. Around the same time, "Super Typhoon" Manghut brought extensive flooding to Guangdong Province, China. Much of the damage in both cases was related to precipitation and runoff into elevated coastal water levels. Mutual interactions between hydrometeorological and ocean models must be advanced in the near future.

The constraints and impacts of urban infrastructure and changing land use patterns must be included in models. The coupling of hydrology models to coastal ocean models is an area of active research and considered by some agencies as a Grand Challenge. To address this challenge, there is an urgent need for multi-institutional models combined with objective test metrics, and innovative forecast products related to flooding of urban coasts at a hierarchy of time and space scales. The goal should be to: *Improve Understanding and Forecasts of Future Compound Inundation Events Affecting Urban Coasts and Related Socio-economic Vulnerabilities.* This will initially involve identifying and assessing the relative impacts of urban flooding under different regimes and designing innovative models to predict future threats. This should be accompanied by effective communication with local, regional and state planners and policy makers concerning specific needs and challenges. NOAA's U.S. IOOS Program Office has sponsored programs such as the Coastal and Ocean Modeling Testbed (COMT; Luettich et al., 2013, 2017) to transition advances by the modeling research community to the community at large, especially partners such as U.S. IOOS Regional Associations, NOAA Center for Operational Oceanographic Products and Services, U.S. Geological Survey (Verdi et al., 2017), Environmental Protection Agency, and U.S. Army Corps of Engineers.

These collaborative efforts have helped to improve emergency preparedness on a synoptic forecast scale. However, additional collaboration will be required to develop coupled models of hydrologic and ocean flooding in order to understand the probabilities and effects of events such as hurricanes Harvey (2017) in the Houston area, Irma (2017) in Jacksonville, Florida, Florence (2018) along the coast of the Carolinas and Michael (2018) on the Florida panhandle. The outcomes of the observing and modeling communities working together via a common platform provide not just better models, but improved observations as the modelers define what observations they need to improve the model performance.

EVOLVING STRATEGIES FOR IMPROVING COASTAL RESILIENCE

On a synoptic forecast scale, pre-event preparations typically involve actions such as evacuation operations, pre-positioning materials, and the operation of water-control and transportation infrastructure. At this time scale, models and data assimilation play important roles in maximizing the utility of available resources and minimizing loss of life. However, there is often little that can be done on this time scale to prevent or reduce damages to the built environment and the natural environment. Thus, in addition to improving modeling and sensor technology, new strategies for rapidly disseminating data for adaptive management purposes must be developed. This will be particularly important at the local level. The preparation of the populations to coastal hazards through outreach is particularly important. To be effective, education of the populations exposed to the danger must be prepared well in advance of events. While reminders of past events such as flooding are important, it is also necessary to convince stakeholders that future threats may be more severe than those they remember. Understanding the sensibility of communities in the face of coastal hazards is crucial when designing risk management plans.

Most oceanographic data assimilation related to resilience is currently associated with forecast-scale operations. Although this can be extremely valuable to decision-making and for overall guidance at event time scales, the application of coastal observations for improving objective model validation in long-term planning scales has not received the same level of attention. Models cannot replace measurements without introducing large uncertainties and biases into critical decisions. Most models today contain numerous parametric approximations and empirical coefficients. Careful tuning of coefficients is often performed after a devastating event in forensics studies, but it has been found that these coefficients must be varied significantly to obtain optimal performance at different sites and for different events. There is a need for more focus on high-quality, event-based measurements as well as long-term data sets. Many deficiencies in today's models have been identified with respect to the physics of nearshore processes. On time scales relevant to long-term planning, potential landscape and ecosystem evolution remains speculative, adding uncertainty to predictions of change in both environmental and anthropocentric factors such as economic and community health. Predictions of waves, surge, and pollutant transport are better than models of coastal evolution.

The overall balance of effort expended on fixed measurements should place more emphasis on event-based sampling. This will require the development of an integrated suite of instruments that could function over a substantial range of spatial and temporal scales in estuarine, riverine, and open-coast environments as well as on flooded lands and roads. Such instrumentation suites would have to be deployable within 24 h and contain sufficient quality and number of sensors within an integrated telemetering and self-recording system (an event-based *infosphere*) to provide needed data to validate the physics and numerical approximations imbedded in models. The potential contribution of such measurements to improved modeling systems and predictions for resilience cannot be overstated. As noted in section "Next Generation Coastal Data Acquisition" observing future environmental changes in coastal urban areas will require new sensors along with new data pathways and workflows that enable a range of users to collect data and that allow data to be centrally processed for quality control and utility. Some of the phenomena to be observed must include the following:

- Storm surge
- Hydrology
- Pluvial flooding
- Compound flooding
- Water quality
- Socio-economic behavior and vulnerability
- Pathogens and pollutants
- Urbanization and urban renewal trends
- Urban and coastal management principles and practices

Obtaining the needed observations from coasts and coastal communities in developing countries where the threats and vulnerabilities are most acute is a serious challenge but one that must be overcome with the help of international organizations. Some potential strategies are discussed in the following section "Data Intensive Infrastructure for Rapid Dissemination of Information." Coastal slums in impoverished coastal megacities require global assistance to become even modestly resilient through improved forecasts.

DATA INTENSIVE INFRASTRUCTURE FOR RAPID DISSEMINATION OF INFORMATION

Digital connectivity is transforming the way humans deal with problems of collective action. Big data-driven applications can improve emergency management efforts during weather-related disasters in coastal areas by integrating human-generated sources with meteorological and oceanographic big data sources. Integrating social and physical sciences is challenging, given the multiplicity of approaches and subjects of study; however, the acceleration of climate change is increasingly demanding creative and integrated solutions to minimize the hazards of weather-related events exacerbated by climate change. This requires multidisciplinary collaboration, multi-sector partnerships, and the expansion of geographic coverage.

Most emergency management "lessons learned" and "best practices" examine biophysical outcomes of disasters rather than the cultural aspects (Weichselgartner, 2001). Given the expansion of digital connectivity and the increased computational capacity for collecting, storing, and analyzing millions of bits of online data related to human activity, combined social media and biophysical data will improve knowledge about collective action during these weather-related emergencies and to enhance emergency response efforts (e.g., coordination efforts, dissemination of information, identification of critically affected areas). While information about emergency and disaster situations has always been transmitted via different types of media networks, the explosion of human-generated online content has led to a shift in how these networks operate and how crisis-related information is disseminated (Ripberger et al., 2014). Understanding disaster-related communications spread across online social networks is key to assisting emergency management agencies in improving disaster response and coordinating messaging (Hossmann et al., 2011; Kongthon et al., 2012; Gomez-Rodriguez et al., 2013; Saleem et al., 2014; Edwards et al., 2015; Kogan et al., 2015; Rudat and Buder, 2015).

Recent interdisciplinary research has demonstrated the utility of new sources of big data for understanding social processes and generating insights that were previously impossible (Boyd and Crawford, 2012, p. 663). Despite the importance of human-generated big data such as social media, during emergency management situations, there remains a gap between the ability of social and computational scientists to analyze these patterns ex post facto and the ability of emergency management agencies to make use of this data in real-time to prepare for, respond to, and recover from emergency events. Algorithms are needed to provide the users of ocean observation systems with improved realizations of unfolding events. Rule-based and statistical approaches to data analytics include situational learning. The Southeastern Universities Research Association (SURA) and partner organizations such as the Florida Institute of Technology, Louisiana State University, Mississippi State University, and University of North Florida are working on contextual adaptation to enhance coastal resilience. The first step requires a big data needs assessment among interested parties, followed by capacity building to access and analyze big data sources.

One of the biggest impediments to emergency managers and other public officials making use of social media data is its relative inaccessibility and relevance to a particular decision-making issue. While use of social media platforms is free, the ability to scrape and analyze raw data generated by or within these platforms is quite costly. Unlike some other platforms, Twitter makes a subset of its data freely available via its Application Programming Interface (API). However, using the Twitter API requires technical insights that many emergency management agencies are unlikely to have. And while a number of scholars have developed dashboards or other systems for collecting and storing large amounts of this data for social research (Stefanidis et al., 2013; Felt, 2016; Yang et al., 2016; Poorthuis and Zook, 2017), the Twitter Terms of Service prevents these data from being shared. These limitations create a divide between data producers and those who want to access and analyze data. University developed tools are addressing these limitations by building capacity among interested parties. For example, the Social Science Research Center at Mississippi State University has made a major investment in techniques for accessing and analyzing social media data. The result of this effort is a web-based software application known as the Social Media Tracking and Analysis System that can access Twitter messages worldwide.

It is important to understand the variety of ways that social media are used by individuals during disaster situations and leverage this understanding to better develop and target interventions during emergencies. By optimizing methods for analyzing social media data in the context of emergency management, it is possible to identify approaches most capable of yielding actionable insights in emergency situations. In particular, the interest is in drawing on multiple aspects of Twitter data, analyzing the qualitative content of each tweet, the social networks that each tweet diffuses through, and the particular spaces and places where these tweets are created.

The massive volume of digital information available from social media platforms necessitates automated approaches to analyzing the actual content of these messages (Hopkins and King, 2010). Although interpreting big data is challenging (Shah et al., 2015), understanding the content of large bodies of human-generated messages can provide important information for social scientists, government officials, and first responders during disasters and emergencies. Content analysis of social media can be especially important for understanding the communication environment and providing situational awareness before, during, and after a disaster or emergency. In fact, the use of content analysis to identify information gaps, rumors, and misinformation is a recommended strategy for crisis emergency and risk communication (Centers for Disease Control and Prevention, 2014). Houston et al. (2015) have conceptualized a variety of uses of social media data during a disaster (from preparedness to post-disaster reconnection), and the value of content analyzing Twitter data emerging from disasters has been illustrated in a number of case studies (e.g., Muralidharan et al., 2011; Spence et al., 2015; Takahashi et al., 2015).

In addition to the qualitative content of tweets, a critical aspect is the relational nature. The networked structure of social media makes it possible to think of it as a mechanism to improve dissemination of information in the context of disaster and emergency response (Magsino, 2009; Jones and Faas, 2016). The goal of network analysis is to map or describe the array of relationships between a set of objects, or nodes (Kadushin, 2012). Given the expansion of internet-based social networks and increased computational capacity for data collection and analysis of these platforms, Social Network Analysis (SNA) allows us to obtain useful information from the large number of relationships within this data. In the context of disaster and emergency response this analysis can improve information propagation throughout a given social network. This can facilitate quicker relays of information, or combat misinformation before it spreads.

Using geographic information systems and spatial analytical techniques, spatially referenced big data can inform responders as to where disasters have occurred and where people might need assistance (Crooks et al., 2013; Kent and Capello, 2013). When combined with the network and content analyses, the spatial analysis of human-generated big data can reveal whether differences in social networks, information diffusion and messaging are shaped by spatial proximity or by some other form of place-based process (Starbird and Palen, 2010; Shelton et al., 2014; Kogan et al., 2015). Because disasters and emergency response situations are intensely place-based events, the addition of a spatial analysis component is key to understanding how these events are experienced and managed by everyday people and governmental agencies, which may not always be in sync, especially when underrepresented or marginalized groups are heavily affected (Crutcher and Zook, 2009; Mulder et al., 2016).

STRATEGIES FOR COASTAL RISK ASSESSMENT AND ADAPTIVE MANAGEMENT

In order to enhance coastal risk assessment and adaptive management, we advocate the establishment of partnerships that transcend geographic and disciplinary boundaries. Partnerships that include representatives from state and federal agencies, non-profits, conservation groups, and the business, health, and industry sectors provide an effective constituency for the needed information. These data provide the basis to develop a conceptual framework for coastal risk assessment in a structured process that is based on the specification of geographic patterns of hazards overlaid by patterns of vulnerability (life-loss, damages, critical infrastructure, social hubs, etc.). In this context, the risks can be quantified to meet the needs of a variety of stakeholders who must make data-driven decisions. The value of accurate estimation and the consequences of inaccuracies in the hazard and risk estimations make a strong case for a unified approach to this issue. A good example of this is the dramatic rise in losses and casualties due to natural disasters such as storm-surge-induced flooding, seismic hazards and tsunami incidence along many coasts over the past few decades that has prompted global concern on impacts and mitigation strategies (Wright and Nichols, 2019). Marine scientists analyze and forecast coastal changes such as regionally varying sea level rise (e.g., Thompson et al., 2014, 2016). Government officials have already started to plan for sea-level rise by completing coastal hazard assessments and developing maps showing areas which are expected to be affected over the next 50–100 years. In some cases, these planning guides support activities such as restricting development in areas prone to coastal erosion, moving structures away from the coast, and discouraging the construction of shore protection.

Government organizations including ocean and meteorological agencies (e.g., Australian Bureau of Meteorology, METEO France, and NOAA), local universities, businesses, and citizens have provided discoverable data from networked sensors that are included as big data resources which can support decision makers. These data come in various forms including historical archives from national data centers, *in situ* data from the neighbor's weather station to ocean observing systems, handheld to satellite imagery, and numerical model output. Users need to sift through data from local, national, and globally available datasets that can help address environmental issues, ranging from recurrent flooding to sea level rise. Local university researchers are already applying new technologies such as unmanned vehicles to fill data gaps that may mask important processes, providing algorithms as evidenced by the COMT, and are defining levels of uncertainty in the data that are available for analysis (Luettich et al., 2017). Private sector companies are also applying big data for targeted solutions and predictive power such as apps that provide weather data to commercial and recreational fishermen. Crowd-sourcing and citizen science like the Hawaiian and Pacific Islands King Tide Project and Geofeedia – a social media intelligence platform that associates social media posts with geographic locations – are increasingly popular tools for creating information where there previously was none. Open hardware and software are expanding to offer widely distributed, inexpensive tools to enable crowd-sourced data collection and analysis.

Coastal risk assessment and adaptive management can employ big data to resolve spatially and temporally variable phenomena that impact coastal communities. Environmental phenomena such as flash floods manifest themselves quickly whereas sea level rise is slow. Big data include historical information, *in situ* data, imagery, and model output. Next generation tools will need to aggregate these vast amounts of data to aid decisions. Baseline information will be key to identifying the magnitude of current changes in coastal processes. Government funded infrastructure such as the National Ecological Observatory Network, Long-term Ecological Research stations, and the U.S. IOOS should collaborate to improve our understanding about issues such as sea level rise, recurring flooding, land use change, harmful algal blooms, hypoxia, and invasive species impacts. These efforts require the sharing of data through open automated resources at both national and international levels. Through this collaboration, next generation models, and data analytics can be applied in an iterative decision-making process. Research is still needed on contextual explanatory models that are reflective of real-world situations. For example, through "on the fly" skill assessments, operational users can select the best model to use for their particular applications.

COMMUNICATING KNOWLEDGE AND PREDICTIONS TO DECISION MAKERS AND THE PUBLIC

Technology solutions and information sciences must be refocused to provide cities, localities, city planners, port engineers, and emergency responders with both specific actionable information that meets the specific needs of that decision maker and anticipates global changes. This information is based on structured and unstructured data, but to be actionable it must be communicated to decision makers in non-technical language and readily understood graphics. Disparate sources of data are gathered from data centers (historical information), IoT sensors (*in situ* data from weather stations, buoys, drifters), aircraft and satellites (remotely sensed imagery), and environmental prediction centers (numerical models). All are essential to providing situational awareness for decision making. Trying to make sense of the coastal zone is a complex challenge. University and institutional researchers have developed a plethora of solutions, tools, and services to help fuse the disparate data to predict events such as inundation with greater certainty.

Understanding of information requirements on different time scales is crucial to future success since the stakeholder's operations are impacted differently at these scales. Typical needs can be partitioned into four contiguous scales: pre-storm preparation; during-storm information and reaction, post-storm recovery and long-term planning. Successful applications require an understanding of each stakeholder's mission, objectives, and definition of success before implementing a technological approach. Stakeholders are diverse, not only in terms of their requirements but in their capacity to participate. For example, communities in developing areas may not have access to data or the resources required to act on the information provided. Stakeholder's requirements are constantly evolving and applications should as well.

Processes that include artificial intelligence, via Deep Learning approaches, may meet some future requirements to support forecasting and response to extreme events. Fused data, where multiple data streams are merged to give local context (for example stream heights contextualized by local levee heights), are more usable by first responders. This type of value-added information can increase the speed and effectiveness of response. AI systems that can interconnect engineering, environmental, and community systems and provide contextualized data as information, enhances the effectiveness of decision-makers and first responders. There is considerable value in having strong relationships between researchers working on AI, such as through a local university or research agency, and local first responders. In this way, research can be linked to response and expertise transferred to state and local programs.

Large datasets culled from data centers, ocean observing systems, model centers, and imagery libraries can easily grow to a size beyond the analytical capability of common software tools and single researchers. To fully utilize the potential of big data requires dedicated resources and expertise. Margaret Davidson, the former director of today's NOAA Office for Coastal Management, recommended the establishment of a collaborative virtual community focusing on data intensive computing to integrate physical and social sciences and improve coastal resilience – a facility that she called a "collaboratorium." This virtual infrastructure for data intensive analysis would integrate diverse teams of scientists and also leverage cloud-based infrastructure, storage, networks, high performance computing, heterogeneous multi-provider services integration, data centric service models, and security for trusted infrastructure and data processing and storage. The collaboratorium would be designed to collect and process high-volume, high-velocity, high-variety data to develop effective and innovative forms of data. Collaborators will share information processing (analytics) for enhanced process control, insight, and decision making. This idea of dedicated centers or environments, where resources, expertise, data and robust use cases, can be brought together to transition research-based systems into operational or semi-operational systems.

The French National Research Infrastructure (FNRI) Data and Services Center for Earth System Modeling offers an example of a data management and dissemination system.

This system is intended to serve primarily the French research community. However, the products also have international aims (satellite missions, global observing networks, partnership for development). The FNRI products are defined and elaborated under the guidance of experts to ensure that they agree with the highest scientific and technical standards. Data series and products from observing networks, *in situ* campaigns and satellite missions, will be qualified, described, and interoperable. The FNRI also provides tools for data discovery, visualization, extraction, and processing, as well as computing resources. To encourage sharing information, good practices and to contribute to the scientific and technical training of the user community, the FNRI has developed collaborative platforms for marine data (e.g., ODATIS).[3] Data and information distributed by the FNRI are important for the implementation of public policies. Developments using these data have important socio-economic impacts on domains such as natural hazards, climate change, and natural resources. The data centers contributing to the FNRI are spread over different regions where they participate in the development of

[3]https://www.odatis-ocean.fr/en/

Subject Matter Experts who can exploit their data to generate environmental intelligence.

CREATING A COLLABORATIVE ENVIRONMENT TO ENHANCE COASTAL RESILIENCE

There is a clear societal need for increased collaboration that leads to improved understanding and mitigation of extreme events. This will require "the science of collaboration" among observational groups, modelers, stakeholders, and others to meet critical future needs in coastal areas. Wright and Thom (2019) describe some of the challenges of promoting effective coastal resilience collaboration as well as some of the approaches that may help overcome those challenges. Especially important is the communication of research results to stakeholders from the community. In addition to traditional modes of collaboration, the Southeastern Universities Research Association (SURA) has implemented a collaborative virtual environment to complete big science projects such as the Southeastern Coastal Ocean Observing and Predicting Program (SCOOP) and the Coastal and Ocean Modeling Testbed (COMT) supported by the NOAA IOOS Office. Both projects required the accomplishment of multidisciplinary and integrated tasks completed by university, government, and industry participants that were spread throughout the United States and Canada. Typical components used to share information and integrate results in a collaborative virtual environment were distributed databases, open source models, webinars, and other types of collaborative software. Important software applications were components of the COMT cyberinfrastructure that were designed to promote data sharing of seminal datasets. In its recent report on community resilience pertaining specifically to the Gulf (of Mexico) Research Program (GRP), the National Academies of Sciences, Engineering, and Medicine, (2019, p. 83) recommends: "*The GRP should create a resilience learning collaborative for stakeholders to exchange information, approaches, challenges, and successes in their respective and collective work to advance community resilience in the Gulf region. The collaborative participants should include government (local, state, federal levels), industry, academia, and other organizations engaged in addressing community resilience.*"

Another prominent example of a collaborative program is the French OSIRISC project: Toward an Integrated Observatory of Coastal Risk and erosion and submersion. The French researchers follow a systemic approach to vulnerability in order to better understand hazards, improve management, and mitigate the associated impacts on populations and other stakes. This interdisciplinary, systemic approach has demonstrated success in addressing the coastal risks of erosion and floods. The evolution of coastal vulnerability over time – whether due to anthropogenic or natural forcing – is readily observable in the present context of climate change and sustained growth of the exposed stakes on coastal territories. Whereas the monitoring of coastal hazards is benefiting from new sensors and data centers, methodologies and tools that allow the assessment of trends, and the management of individual and social representations of risk are still limited.

To address the need for a coherent coastal vulnerability evaluation framework for the benefits of both academics and stakeholders, the OSIRISC project (2017–2019) offers a methodology dedicated to the interdisciplinary observation of the coastal risks of erosion and flooding. OSIRISC focuses specifically on:

(1) The elaboration of indicators describing these components.
(2) The integration of such indicators into a web-based interface with high spatial resolution.
(3) An iterative testing process bringing together coastal risk experts (researchers, stakeholders, land use managers) at the French regional level, in Brittany.

Key to realizing the promise of virtual collaboration is the assignment of collaboration leaders. These individuals facilitate interaction among participants regardless of location and organization to mine the collective wisdom of a widely dispersed group of researchers. Collaboration leaders need to focus on methods that get virtual teams to bond in order to create meaningful dialogue, share successes, and avoid misunderstandings. Collaboration leadership was important to establishing unwritten agreements related to communications and decision-making and building virtual trust on SURA's big science projects. Trust among the various partners grew out of SCOOP and expanded with COMT. One key element facilitating collaboration involved the planning and execution of the annual COMT PI and Partners meeting. Such meetings facilitate strong collaborations across research communities and federal agencies.

Creating a new generation of virtual collaborative environments encourages innovation and allows diverse perspectives to be leveraged and to connect interdisciplinary researchers. Collaborative demonstrations with stakeholders in parallel with research and development are essential to prepare, resist, recover, and adapt to extreme events and long-term change. By building team confidence in the abilities of its members and establishing specific strategies for knowledge sharing, the diversity of perspectives on collaborative teams can be more readily accessed. Leadership must ensure that virtual collaboration stays focused and that project goals are accomplished in a timely and cost-effective manner. Furthermore, community support and acceptance are essential. Hence, next generation observatories for coastal resilience and adaptation should invest in outreach to and nurturing of citizen scientists.

VISION FOR FUTURE SUPPORT OF COASTAL RESILIENCE INITIATIVES

The global coastal science community should develop a vision for 2029 for observations and systems that promote and enhance coastal resilience and adaptation and meld the following enhancements into a framework for delivering new outcomes:

(1) Increased collection of coastal observation data through use of satellites, traditional observing programs, smart-city projects such as the *StormSense* network in Hampton Roads, Virginia, and cheap sensor or mobile-phone-based citizen science projects via community, NGO's or other groups;
(2) Implementation of new sensors including satellite constellations such as *Kinesis*, cheaper water level sensors, sensors for pollutants and contaminants and for biological responses such as Harmful Algal Blooms, organized as sensor webs using IoT principles for data collection and analysis;
(3) Use of social media both as a valuable input data source and as a means of delivering targeted information about alerts, risks and responses;
(4) A better understanding of how humans react to and utilize emergency response data and information to ensure that the social science around public level emergency response is understood so that new tools and approaches provide outcomes not just information;
(5) Development of better models through collaborative environments, such as COMT, where models can be developed, validated, assessed and operationalized;
(6) Use of AI as a fundamental tool for bringing together a range of disparate data of varying levels of quality and type for processing for input into models and to constrain outputs to actionable information;
(7) A method of collecting on ground data during events, via trained first responders or equivalent, to better force models and ensure that model outputs are relevant and of use;
(8) Virtual collaborative environments, aka "collaboratoriums," that bring together the latest advances in computing, in data science, in observational science, in social science, environmental science, engineering and policy to address particular end-user use-cases with the goal of undertaking the research and development required to deliver new types of information, tools and understandings.
(9) An objective evaluation of models at all locations following events to identify issues that may compromise predictions. Comparisons should be done by a collaborative group that collects the observations independent of operational groups that produce the model results.
(10) Improved use of derived information and development of enhanced technologies for post-event recovery.
(11) It is critical for additional information to be collected during extreme events. The sparse estimates of waves and water levels, often after the events, does not allow a rigorous evaluation of model physics and numerical methods.

Figure 4 shows how the various components of a collaborative system might interconnect to provide a single framework to promote and enhance coastal resilience. Future plans should leverage resilience efforts that are focused on threats common to a geographic region through sustained educational and outreach programs that help develop stakeholders from the private, public, and university sectors. A seminar series is essential to promote the inclusion of powerful partnerships extending from local to regional scales that leverage big data resources and viable data analytics. Develop a website that connects coastal resilience resources to facilitate progress in a field that is already developing globally. The website should feature digital scholarship developed by natural and social scientists, especially results from grand challenges such as the coupling of inundation and social "urban planning" models. This website will provide a foundation for progress and the development of fully integrated partnerships that include government, university, and industry members. There should be provision for limited objective experiments that allow partnership assessment and evaluation of approaches that best achieve integrated environmental, engineering, and community resilience results at the local level. These experiments would apply data that includes historical information, *in situ* observations, imagery, and numerical models. Based on local successes, they would provide an opportunity for the planning and execution of regional-scale research experiments where science-based results can be demonstrated to benefit a large geographic region, one that might include observational networks such as the National Science Foundation (NSF) Long-term Ecological Research Network, NOAA's U.S. IOOS, and the NSF Ocean Observing Initiative. Importantly, rapidly deployable *in situ* observations should be collected to characterize extreme events. A capstone demonstration should be conducted that allows for the objective assessment of research results by operational users from local emergency responders and federal stakeholders.

RECOMMENDATIONS

Observing systems, coupled with models and information dissemination subsystems, can provide the environmental intelligence to allow coastal communities to adapt to long-term coastal degradation and short-term catastrophic events. Many of the required components already exist or are in development. The main need is for networks to connect observers, modelers, managers and first responders so that solutions can flow across disciplinary and stakeholder boundaries. This already includes connecting observing and modeling communities. For new developments in understanding and predicting to enhance the resilience of coastal communities in the future, more attention needs be devoted to education of, and outreach to, the affected communities and their leaders.

Some challenges that still need to be addressed include the following:

- New observing systems, including satellites, sensors, and collection mechanisms, such as community driven data collection, should be developed using the frameworks from the IoT, to allow for large scale collection and analysis of data including fundamental base-line data and maps.
- To facilitate the development of new models and information systems, including AI approaches to big data, there is a need for better integration of data during

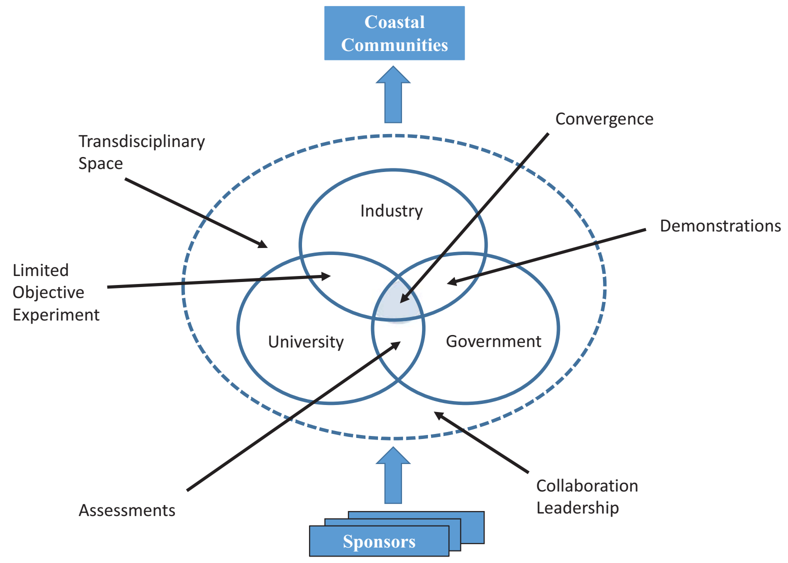

FIGURE 4 | Fully integrated projects should include stakeholders from government, academia, and industry. Collaboration leadership brings together the environmental scientists, engineers, and community to develop the theoretical foundations of coastal resilience through integrated research and training activities. Arrows indicate the flow of progress toward developing more resilient communities.

extreme events to deliver outcomes suitable for decision makers and first responders.

- Development of "collaboratoriums," will allow observing, modeling, informatics, management, and response communities to connect. Results will foster better strategies and systems, validate and operationalize models and facilitate coordination among communities, nationally and internationally.
- Collaboration leaders must be equipped to help science groups and teams meet the challenges of collaborating across organizations, regions, and nations.
- Information products and prediction, including baseline data sets, infrastructure and expertise, must be made available to developing or resource poor countries that, in many cases, have much of the high-risk coastline and host many of the 16 coastal based mega-cities.

The constraining issues are not primarily technical but organizational. Coastal resilience is important to all countries at some level and so the task is to take best practice from organizations around the world and deliver outcomes that enhance our ability to maintain and sustain our coastal communities. Coastal communities are at the forefront of climate change impacts including short term events and longer-term trends. Community resilience requires new approaches to the collection of observing data and new methods for data dissemination. The challenge is to develop collaborations and projects that bring all of the parties together to ensure that coastal communities can implement resilient strategies. Regionally specific coastal resilience seminars and workshops can identify optimal areas to plan transdisciplinary experiments. Such workshops allow stakeholders and science teams, to share views for selected projects while deepening the researcher's grasp of issues and priorities.

AUTHOR CONTRIBUTIONS

CN initiated the preliminary draft, added materials along the way, and made edits for the entire white paper. LW facilitated the collaborative writing, ensured citations of the recent work, and made substantial edits. AC and GM contributed to the big data sections. LC coordinated the input from AH, PL, and NLD contributions on the Université de Bretagne Occidentale resilience research, Eurosion, and edits. SB contributed to the AIMS material and made excellent edits that enhanced the final manuscript. JDL and SK provided results and text concerning the Storm sense program. AH, PL, NLD, and LC conducted research and provided text on the French programs. DR made important changes related to the modeling and nearshore processes. GZ helped with the organization and added nearshore and coast type perspectives.

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REFERENCES

Bachmann, C. M., Rehman, S. E., Lapszynski, C. S., Badura, G. P., Vodacek, A., Hoffman, M. J., et al. (2019). A low-rate video approach to hyperspectral imaging of dynamic scenes. *J. Imaging* 5:6. doi: 10.3390/jimaging501000

Bannister, N. P., and Neyland, D. L. (2015). Maritime domain awareness with commercially accessible electro-optical sensors in space. *Int. J. Remote Sens.* 36, 211–243. doi: 10.1080/01431161.2014.990647

Bernatchez, P., and Fraser, C. (2012). Evolution of Coastal defense structures and consequences for beach width trends, Québec, Canada. *J. Coast. Res.* 28, 1550–1566. doi: 10.2112/jcoastres-d-10-00189.1

Blackburn, S., and Pelling, M. (2014). Coastal megacities: risks and opportunities. *IGBP Glob. Chang. Magaz.* 82, 8–11.

Boyd, D., and Crawford, K. (2012). Critical questions for big data: provocations for a cultural, technological, and scholarly phenomenon. *Inform. Commun. Soc.* 15, 662–679. doi: 10.1080/1369118x.2012.678878

Camfield, F. E., and Morang, A. (1996). Defining and interpreting shoreline change. *Ocean Coast. Manag.* 32, 129–151. doi: 10.1016/s0964-5691(96)00059-2

Carter, R. W. G. (1988). *An Introduction to the Physcial, Ecological, and Cultural Systems of Coastlines*. London: Academic Press Limited.

Cazenave, A., Cozannet, G., Le Benveniste, J., Woodworth, P. L., and Champollion, N. (2017). *Monitoring Coastal Zone Changes From Space*. Lisbon: EOS.

Centers for Disease Control and Prevention (2014). *Crisis and Emergency Risk Communication*. Washington, DC: U.S. Department of Health and Human Services.

Crooks, A., Croitoru, A., Stefanidis, A., and Radzikowski, J. (2013). Earthquake: twitter as a distributed sensor system. *Trans. GIS* 17, 124–147. doi: 10.1111/j.1467-9671.2012.01359.x

Crutcher, M., and Zook, M. (2009). Placemarks and waterlines: racialized cyberscapes in post-Katrina google earth. *Geoforum* 40, 523–534. doi: 10.1016/j.geoforum.2009.01.003

Cutter, S. L., Ash, K., and Emrich, C. (2014). The geographies of community disaster resilience. *Glob. Environ. Chang.* 29, 65–77. doi: 10.5055/jem.2014.0165

Cutter, S. L., Burton, C. G., and Emrich, C. T. (2010). Disaster resilience indicators for benchmarking baseline conditions. *J. Homeland Secur. Emerg. Manag.* 7:51. doi: 10.2202/1547-7355.1732

Dawson, A. (2017). *Extreme Cities: The Perils and Promise of Urban Life in the Age of Climate Change*. New York, NY: Verso, 378.

d'Ercole, R., and Pigeon, P. (1999). L'expertise internationale des risques dits naturels: intérêt géographique/Geographical relevance of natural risk assessment on an international scale. *Ann. Géogr.* 608, 339–357. doi: 10.3406/geo.1999.21777

Doornkamp, J. C. (1998). Coastal flooding, global warming and environmental management. *J. Environ. Manag.* 52, 327–333. doi: 10.1006/jema.1998.0188

Edwards, J. F., Mohanty, S., and Fitzpatrick, P. (2015). *Assessment of Social Media Usage During Sever Weather Events and the Development of a Twitter-Based Model for Improved Communication of Storm-related Information*. Starkville, MS: NOAA.

Felt, M. (2016). Social media and the social sciences: how researchers employ big data analytics. *Big Data Soc.* 3, 1–15.

Flanagan, B. E., Gregory, E. W., Hallisey, E. J., Heitgerd, J. L., and Lewis, B. (2011). A social vulnerability index for disaster management. *J. Homeland Secur. Emerg. Manag.* 8:3. doi: 10.2202/1547-7355.1792

Gesch, D. B. (2018). Best practices for elevation-based assessments of sea-level rise and coastal flooding exposure. *Front. Earth Sci.* 6:230. doi: 10.3389/feart.2018.00230

Gomez-Rodriguez, M., Leskovec, J., and Schölkopf, B. (2013). "Structure and dynamics of information pathways in online media," in *Proceedings of the Sixth ACM International Conference on Web Search and Data Mining*, (New York, NY: ACM), 23–32.

Guillard-Gonçalves, C., Cutter, S. L., Emrich, C. T., and Zêzere, J. L. (2014). Application of social vulnerability index (SoVI) and delineation of natural risk zones in greater lisbon. Portugal. *J. Risk Res.* 18, 651–674. doi: 10.1080/13669877.2014.910689

Guillot, B., Castelle, B., Marieu, V., Bujan, S., and Rosebery, D. (2018). "UAV Monitoring of 3 year foredune partial recovery from a severe winter: Truc Vert beach," in *Proceedings from the International Coastal Symposium (ICS) 2018*, eds J.-S. Shim, I. Chun, and H. S. Lim Busan, 276–280. doi: 10.2112/si85-056.1

Gunderson, L. H., and Holling, C. S. (2002). *Panarchy: Understanding Transformations in Human and Natural Systems*. Washington, DC: Island Press.

Hallegatte, S., Green, C., Nicholls, R. J., and Corfee-Morlot, J. (2013). Future flood losses in major coastal cities. *Nat. Clim. Chang.* 3, 802–806. doi: 10.1111/risa.13285

Hénaff, A. (2017). *Vers un Observatoire Intégré des Risques Côtiers d'érosion-Submersion. Journées du Littoral de la Fondation de France*. Paris: UICP.

Hénaff, A., and Philippe, M. (2014). *Gestion des Risques d'érosion et de Submersion Marines. Guide Méthodologique*. Available at: http://www.risques-cotiers.fr/fr/boite-a-outils/guide_cocorisco(accessed November, 2014).

Hopkins, D. J., and King, G. (2010). A method of automated nonparametric content analysis for social science. *Am. J. Polit. Sci.* 54, 229–247. doi: 10.1111/j.1540-5907.2009.00428.x

Hossmann, T., Legendre, F., Carta, P., Gunningberg, P., and Rohner, C. (2011). "Twitter in disaster mode: Opportunistic communication and distribution of sensor data in emergencies," in *Proceedings of the 3rd Extreme Conference on Communication: The Amazon Expedition*, (New York, NY: ACM).

Houston, J. B., Hawthorne, J., Perreault, M. F., Park, E. H., Goldstein Hode, M., Halliwell, M. R., et al. (2015). Social media and disasters: a functional framework for social media use in disaster planning, response, and research. *Disasters* 39, 1–22. doi: 10.1111/disa.12092

Jones, E. C., and Faas, A. J. (eds). (2016). *Social Network Analysis of Disaster Response, Recovery, and Adaptation*. Oxford: Elsevier.

Kadushin, C. (2012). *Understanding social networks: Theories, concepts, and findings*. Oxford: Oxford University Press.

Kent, J. D., and Capello, H. T. Jr. (2013). Spatial patterns and demographic indicators of effective social media content during the Horsethief Canyon fire of 2012. *Cartogr. Geogr. Inform. Sci.* 40, 78–89. doi: 10.1080/15230406.2013.776727

Kogan, M., Palen, L., and Anderson, K. M. (2015). "Think local, retweet global: Retweeting by the geographically-vulnerable during Hurricane Sandy," in *Proceedings of the 18th ACM Conference on Computer Supported Cooperative Work & Social Computing*, (New York, NY: ACM), 981–993.

Komar, P. D., and McDougal, W. G. (1988). Coastal erosion and engineering structures: the Oregon experience. *J. Coast. Res. Spec. Issue* 4, 77–92.

Kongthon, A., Haruechaiyasak, C., Pailai, J., and Kongyoung, S. (2012). "The role of Twitter during a natural disaster: Case study of 2011 Thai Flood," in *Proceedings of PICMET'12Technology Management for Emerging Technologies (PICMET)*, (Piscataway, NJ: IEEE), 2227–2232.

Kovacs, E., Roelfsema, C., Lyons, M., Zhao, S., and Phinn, S. (2018). Seagrass habitat mapping: how do Landsat 8 OLI, Sentinel-2, ZY-3A, and Worldview-3 perform? *Remote Sens. Lett.* 9, 686–695. doi: 10.1080/2150704X.2018.1468101

Luettich, R. A. Jr., Wright, L. D., Nichols, C. R., Baltes, R., Friedrichs, M. A. M., Kurapov, A., et al. (2017). *A Test Bed for Coastal and Ocean Modeling*. Lisbon: EOS.

Luettich, R. A., Wright, L. D., and Signell, R. (2013). Introduction to special section on the U.S. IOOS Coastal and Ocean modeling testbed. *J. Geophys. Res. Oceans* 118, 6319–6328. doi: 10.1002/2013JC008939

Magsino, S. L. (2009). *Applications of Social Network Analysis for Building Community Disaster Resilience*. Washington, DC: National Academy of Sciences.

Marcel, O., Le Berre, I., Rouan, M., Philippe, M., and Hénaff, A. (2018). *Une Application WEB- SIG de Suivi de la Vulnérabilité Systémique des Littoraux (Projet OSIRISC)*. Plouzané: Ifremer.

Meur-Férec, C., Deboudt, P., Deldrève, V., Flanquart, H., Hellequin, A.-P., Herbert, V., et al. (2003–2004). *La Vulnérabilité des Territoires Côtiers: Évaluation, Enjeux et POLITIQUES Publiques*. France: Programme National Environnement Côtier (PNEC).

Meur-Férec, C. (2006). *De la Dynamique Naturelle à la Gestion Intégrée de L'espace Littoral: Unitinéraire de Géographe. Géographie*. Nantes: Université de Nantes.

Meur-Férec, C. (2008). *De la Dynamique Naturelle à la Gestion Intégrée de L'espace Littoral: Unitinéraire de Géographe*. Paris: Edilivre, 250.

Meur-Férec, C., and Morel, V. (2004). L'érosion sur la frange côtière: un exemple de gestion des risques. *Nat. Sci. Soc.* 12, 263–273. doi: 10.1051/nss:2004038

Michel-Guillou, E., and Meur-Féréc, C. (2017). Representations of coastal risk (erosion and marine flooding) among inhabitants of at-risk municipalities. *J. Risk Res.* 20, 776–799. doi: 10.1080/13669877.2015.1119181

Mulder, F., Ferguson, J., Groenewegen, P., Boersma, K., and Wolbers, J. (2016). Questioning big data: Crowdsourcing crisis data towards an inclusive humanitarian response. *Big Data Soc.* 3:2053951716662054.

Muralidharan, S., Rasmussen, L., Patterson, D., and Shin, J. H. (2011). Hope for Haiti: an analysis of facebook and twitter usage during the earthquake relief efforts. *Public Relat. Rev.* 37, 175–177. doi: 10.1016/j.pubrev.2011.01.010

National Academies (2012). *Disaster Resilience: A National Imperative. Report of Committee on Increasing National Resilience to Hazards and Disasters*. Washington DC: National Academies Press, 260.

National Academies of Sciences, Engineering, and Medicine (2019). *Building and Measuring Community Resilience: Actions for Communities and the Gulf Research Program*. Washington, DC: The National Academies Press.

Norris, F., Stevens, S., Pfefferbaum, B., Wyche, K., and Pfefferbaum, R. (2008). Community resilience as a metaphor, theory, set of capacities, and strategy for disaster readiness. *Am. J. Commun. Psychol.* 41, 127–150. doi: 10.1007/s10464-007-9156-6

Parente, C., and Pepe, M. (2018). Bathymetry from worldView-3 satellite data using radiometric band ratio. *Acta Polytech.* 58, 109–117. doi: 10.14311/AP.2018.58.0109

Paskoff, R. (1993). *Côtes en Danger*. Paris: Masson.

Paskoff, R. (1998). *Les Littoraux, Impacts des Aménagements Sur Leur Évolution*. Paris: Armand Colin.

Pelling, M., and Blackburn, S. (eds). (2014). *Megacities and the Coast: Risk, Resilience and Transformation*. New York, NY: Routledge, 248.

Poorthuis, A., and Zook, M. (2017). Making big data small: strategies to expand Urban and Geographical research using social media. *J. Urban Technol.* 24, 115–135. doi: 10.1080/10630732.2017.1335153

Ranasinghe, R., and Jongejan, R. (eds). (2018). *Climate Change, Coasts and Coastal Risk*. Basel: MDPI.

Reed, A. J., Mann, M. E., Emanuel, K. A., Lin, N., Horton, B. P., Kemp, A. C., et al. (2015). Increased threat of tropical cyclones and coastal flooding to New York City during the anthropogenic era. *Proc. Natl. Acad. Sci. U.S.A.* 112, 12610–12615. doi: 10.1073/pnas.1513127112

Ripberger, J. T., Jenkins-Smith, H. C., Silva, C. L., Carlson, D. E., and Henderson, M. (2014). Social media and severe weather: do tweets provide a valid indicator of public attention to severe weather risk communication? *Weather Clim. Soc.* 6, 520–530. doi: 10.1175/wcas-d-13-00028.1

Rosati, J. D., Touzinsky, K. F., and Lillycrop, W. J. (2015). Quantifying coastal system resilience for the US Army Corps of Engineers. *Environ. Syst. Decis.* 35, 196–208. doi: 10.1007/s10669-015-9548-3

Rudat, A., and Buder, J. (2015). Making retweeting social: The influence of content and context information on sharing news in twitter. *Comp. Hum. Behav.* 46, 75–84. doi: 10.1016/j.chb.2015.01.005

Saleem, H. M., Xu, Y., and Ruths, D. (2014). Novel situational information in mass emergencies: what does twitter provide? *Proc. Eng.* 78, 155–164. doi: 10.1016/j.proeng.2014.07.052

Salisbury, J., Davis, C., Erb, A., Hu, C., Gatebe, C., Jordan, C., et al. (2017). Coastal observations from a new vantage point. *EOS Earth Space Sci. News* 98, 20–25.

Salman, A., Lombardo, S., and Doody, P. (2004). *Living with Coastal Erosion in Europe: Sediment and Space for Sustainability. Part IV—A Guide to Coastal Erosion Management Practices in Europe: Lessons Learned*. Hague: Eurosion, Directorate General Environment European Commission.

Shah, D. V., Cappella, J. N., and Neuman, W. R. (2015). Big data, digital media, and computational social science: Possibilities and perils. *Ann. Am. Acad. Polit. Soc. Sci.* 659, 6–13. doi: 10.1177/0002716215572084

Shang, C., Yang, F., Huang, D., and Lyu, W. (2014). Data-driven soft sensor development based on deep learning technique. *J. Process Control* 242:233.

Shelton, T., Poorthuis, A., Graham, M., and Zook, M. (2014). Mapping the data shadows of Hurricane Sandy: uncovering the sociospatial dimensions of 'big data'. *Geoforum* 52, 167–179. doi: 10.1016/j.geoforum.2014.01.006

Spence, P. R., Lachlan, K. A., Lin, X., and del Greco, M. (2015). Variability in twitter content across the stages of a natural disaster: implications for crisis communication. *Commun. Q.* 63, 171–186. doi: 10.1080/01463373.2015.1012219

Starbird, K., and Palen, L. (2010). "Pass it on?: Retweeting in mass emergency," in *Proceedings of the International Community on Information Systems for Crisis Response and Management*, Seattle, 1–10.

Stefanidis, A., Crooks, A., and Radzikowski, J. (2013). Harvesting ambient geospatial information from social media feeds. *GeoJournal* 78, 319–338. doi: 10.1007/s10708-011-9438-2

Takahashi, B., Tandoc, E. C., and Carmichael, C. (2015). Communicating on Twitter during a disaster: an analysis of tweets during Typhoon Haiyan in the Philippines. *Comp. Hum. Behav.* 50, 392–398. doi: 10.1016/j.chb.2015.04.020

Thompson, P. R., Merrifield, M. A., Wells, J. R., and Chang, C. M. (2014). Wind-driven coastal Sea Level Variability in the Northeast Pacific. *J. Clim.* 27, 4733–4751. doi: 10.1175/JCLI-D-13-00225.1

Thompson, P. R., Piecuch, C. G., Merrifield, M. A., McCreary, J. P., and Firing, E. (2016). Forcing of recent decadal variability in the Equatorial and North Indian Ocean. *J. Geophys. Res. Oceans* 121, 6762–6778. doi: 10.1002/2016JC012132

Van Zandt, S., Peacock, W. G., Henry, D. W., Grover, H., Highfield, W. E., and Brody, S. D. (2012). Mapping social vulnerability to enhance housing and neighborhood resilience. *Hous. Policy Debate* 22, 29–55. doi: 10.1080/10511482.2011.624528

Verdi, R. J., Lotspeich, R. R., Robbins, J. C., Busciolano, R. J., Mullaney, J. R., Massey, A. J., et al. (2017). The surge, wave, and tide hydrodynamics (SWaTH) network of the U.S. Geological Survey—Past and future implementation of storm-response monitoring,data collection, and data delivery. *U.S. Geol. Surv. Circ.* 1431:35. doi: 10.3133/cir1431

Wahl, T., Jain, S., Bender, J., Meyers, S. D., and Luther, M. E. (2015). Increasing risk of compound flooding from storm surge and rainfall for major US cities. *Nat. Clim. Change* 5, 1093–1097. doi: 10.1038/nclimate2736

Weichselgartner, J. (2001). Disaster mitigation: the concept of vulnerability revisited. *Disast. Preven. Manag. Int. J.* 10, 85–95. doi: 10.1098/rsta.2014.0373

Wright, L. D. (2019). "Future Societal Vulnerability, Risk and Adaptability," in *Tomorrow's Coasts: Complex and Impermanent*. Coastal Research Library, eds L. Wright and C. Nichols (Cham: Springer), 293–304. doi: 10.1007/978-3-319-75453-6_18

Wright, L. D., and Nichols, C. R. (eds) (2019). *Tomorrow's Coasts: Complex and Impermanent. Coastal Research Library Series*. Cham: Springer.

Wright, L. D., Nichols, C. R., Cosby, A. G., and D'Elia, C. F. (2016). *Collaboration to Enhance Coastal Resilience*. Lisbon: Eos.

Wright, L. D., and Thom, B. G. (2019). "Promoting Resilience of Tomorrow's Impermanent Coasts," in *Tomorrow's Coasts: Complex and Impermanent. Coastal Research Library*, eds L. Wright and C. Nichols (Cham: Springer), 341–353. doi: 10.1007/978-3-319-75453-6_21

Yang, J. A., Tsou, M. H., Jung, C. T., Allen, C., Spitzberg, B. H., Gawron, J. M., et al. (2016). Social media analytics and research testbed (SMART): Exploring spatiotemporal patterns of human dynamics with geo-targeted social media messages. *Big Data Soc.* 3, 1–19. doi: 10.1177/2053951716652914

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Ocean Time Series Observations of Changing Marine Ecosystems: An Era of Integration, Synthesis, and Societal Applications

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Sustained ocean time series are critical for characterizing marine ecosystem shifts in a time of accelerating, and at times unpredictable, changes. They represent the only means to distinguish between natural and anthropogenic forcings, and are the best tools to explore causal links and implications for human communities that depend on ocean resources. Since the inception of sustained ocean observations, ocean time series have withstood many challenges, most prominently availability of uninterrupted funding and retention of trained personnel. This OceanObs'19 review article provides an overarching vision for sustained ocean time series observations for the next decade, focusing on the growing challenges of maintaining sustained ocean time series, including ship-based and autonomous coastal and open-ocean platforms, as well as remote sensing. In addition to increased diversification of funding sources to include the private sector, NGOs, and other groups, more effective engagement of stakeholders and other end-users will be critical to ensure the sustainability of ocean time series programs. Building a cohesive international time series network will require dedicated capacity to coordinate across observing programs and leverage existing infrastructure and platforms of opportunity. This review article outlines near-term observing priorities and technology needs; explores potential mechanisms to broaden ocean time series data applications and end-user communities; and describes current tools and future requirements for managing increasingly complex multi-platform data streams and developing synthesis products that support science and society. The actionable recommendations outlined herein ultimately form the basis for a robust, sustainable, fit-for-purpose time series network that will foster a predictive understanding of changing ocean systems for the benefit of society.

Keywords: ocean time series, marine ecosystems, climate, end-users, synthesis, sustained observations

INTRODUCTION

Humans depend on the ocean for many goods and services, including fisheries and aquaculture production, natural products, water purification, shoreline protection, transportation, and recreation. Oceanic processes affecting these services vary over a range of time and space scales (**Figure 1**), with anthropogenic forcing contributing an added layer of complexity. In a growing effort to distinguish between natural and human-induced changes, which statistically requires several decades of sustained measurements (Henson et al., 2016), ocean time series from ships, autonomous surface and underwater vehicles, and satellite-based platforms have taken on a greater importance. Long-term ocean observations have already provided unprecedented insights into how marine ecosystems function and how they are changing over a range of temporal and spatial scales.

Sustained time series observations come at a cost, as they require lasting investments in trained personnel, institutions, and infrastructure that facilitate repeat measurements of physical, atmospheric, biological, and biogeochemical variables. However, the payoffs on these investments are significant, as ocean time series data help characterize natural patterns of ocean system variability and associated links to regional climate indices, as well as long-term anthropogenic impacts on marine ecosystems (Neuer et al., 2017). The resulting long-term data sets also provide the mechanistic and observational knowledge of ocean structure and function that form the conceptual basis of Earth System Models, which are in turn critical to forecasting marine ecosystem changes and informing management and policy development (Karl, 2010; Valdés and Lomas, 2017). These data sets also directly support calibration/validation of autonomous *in situ* and remote (satellite, airborne) sensors. In addition to monitoring changes in marine ecosystems, time series programs benefit the oceanographic community by providing data sets to support the scientific goals of countless ancillary projects. Furthermore, ship-based time series, in particular, have long served as invaluable training sites for scientists of all career stages, as testbeds for new technology and methods, and as incubators for interdisciplinary scientific inquiry.

As part of the Global Ocean Observing System (GOOS), the Framework for Ocean Observing (Lindstrom et al., 2012) outlined a strategy for establishing universally accepted sets of Essential Ocean Variables (EOVs), advancing technology, particularly for biological and biogeochemical variables, and integrating across observing programs and platforms to develop products that support science and society. However, it is noteworthy that there is a striking discrepancy between these EOV sets and the core variables that have been measured by keystone ocean time series for over 30 years. Lampitt et al. (2010) highlighted the importance of Eulerian observatories and the need for regional to global arrays in monitoring long-term ocean change. Since then, some of this vision has been realized through the development of networks that integrate observing assets across time and space scales. However, increased international coordination and attention to sustained funding mechanisms are needed to develop a more cohesive ocean time series network and ensure more routine incorporation of ocean time series in products that support science and society. Building on lessons learned and recommendations put forth by Lampitt et al. (2010) and Karl (2010), this OceanObs'19 review article brings much needed attention to the growing challenges of maintaining sustained ocean time series (coastal and open ocean, *in situ*, and remote) and outlines near-term observing priorities and technology development, mechanisms to broaden end-user communities, tools for dealing with increasingly complex multi-platform data streams, and synthesis products as part of an overarching vision for sustained ocean time series. In this paper, we highlight four major themes we view as important areas for development over the coming decade:

(1) Strengthen marine ecological observing capacity through enhancement of shipboard, autonomous, and satellite-based observing assets.
(2) Promote greater integration of ocean time series data and Earth System Models to better understand processes underlying ocean change and improve predictive capacity.
(3) Broaden applications and end-users of ocean time series data.
(4) Foster global collaboration and networking to advance science, expand and improve measurements, and optimize data access.

THE CURRENT OCEAN TIME SERIES MODEL: INSIGHTS AND CHALLENGES

Since the early to mid-20th century, sustained repeat measurements of ocean physics, biology, and biogeochemistry have provided insights into marine ecosystem function and patterns of variability in the ocean. The earliest examples of such observatories include Station E1 of the Western Channel Observatory in the English Channel (1903), Station M in the Norwegian Sea (1948), the California Cooperative Oceanic Fisheries Investigations (CalCOFI) in the California Current System (1949), Ocean Station Papa in the northeast Pacific (1947), Hydrostation S in the Sargasso Sea (1954), and the Boknis Eck Time Series Station in the Baltic Sea (1957). The Joint

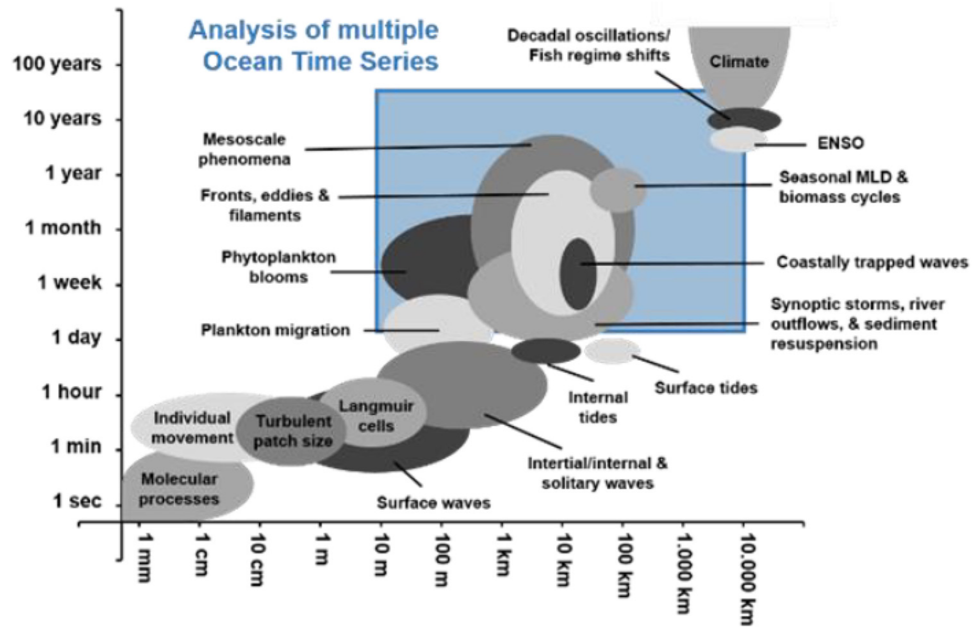

FIGURE 1 | Temporal and spatial scales of a range of ocean processes. The blue square highlights the range of space and time scales that can be addressed by ship-based time series measurements (from Valdés and Lomas, 2017).

Global Ocean Flux Study (JGOFS) era saw the establishment of seven new time series programs, including the Bermuda Atlantic Time-series Study (BATS), European Station for Time series in the Ocean, Canary Islands (ESTOC), DYnamique des Flux Atmosphériques en MEDiterranée (DYFAMED), Hawaii Ocean Time-series (HOT), Kerguelen Point Fixe (KERFIX), Kyodo Northwest Pacific Ocean Time-series (KNOT), and South East Asia Time-Series Station (SEATS), each with its own scientific drivers but all motivated by a common overarching set of JGOFS objectives and implementation procedures, including standard core measurements and protocols, offering ample opportunities for comparative analyses of marine ecosystem state and function (e.g., Karl et al., 2003). Today, ocean time series are operating throughout the global ocean and across multiple platforms, including ship- and shore-based programs, autonomous assets (stationary moorings, free-floating floats, guided gliders, autonomous surface ships, etc.), satellites, and formalized single- and multi-platform observing networks such as the Argo and Biogeochemical-Argo (BGC-Argo) Programs, the Ocean Observatories Initiative (OOI), OceanSITES, the Marine Biodiversity Observation Network (MBON), and the Long-Term Ecological Research (LTER) Program. The aforementioned time series platforms and networks collectively span the broad range of time and space scales needed to query the biological, physical, and chemical states of the ocean and examine links to local, regional, and global-scale processes. Ship-based ocean time series have also increasingly served as test beds for the development of new sensors, methodologies, and calibration/validation sites. They have provided valuable seagoing and hands-on training opportunities for the next generation of ocean scientists, as well as a forum for international collaboration and capacity building.

Insights From Sustained Ocean Time Series Observations

Marine ecosystems are experiencing unprecedented rates of change associated with rising atmospheric carbon dioxide (CO_2) levels and climate change, including concurrent shifts in temperature, circulation, stratification, nutrient input, oxygen (O_2) content, and ocean acidification. Marine food webs comprise a delicate balance among primary producers, intermediate consumers, and top predators. Sustained repeat ocean time series measurements across multiple platforms have documented changes in marine ecosystems over a range of time and space scales in both open ocean and coastal systems.

Changing Ocean Chemistry

The ocean has absorbed 25–30% of the anthropogenic CO_2 emitted since the preindustrial era (Sabine et al., 2004; Gruber et al., 2019). Recent analyses of ocean partial pressure of CO_2 (pCO_2) across multiple independent open ocean shipboard ocean time series sites (**Figure 2**) show increasing acidity across ocean basins over the past 2–3 decades (Bates et al., 2014; Tanhua et al., 2015), demonstrating the global extent of this phenomenon and the importance of high-resolution data sets to remove seasonality and elucidate longer-term trends. In addition to increasing acidity, warming, increased stratification, and circulation changes have reduced O_2 levels, particularly in eastern boundary upwelling systems off southern California, South America, and West Africa (Stramma et al., 2008) (**Figure 3**). The CalCOFI ocean time series has documented a decline in O_2 levels and a shoaling of the oxygen minimum layer over the past 2–3 decades that is likely to affect organisms living in the water column and on the seafloor (Bograd et al., 2008).

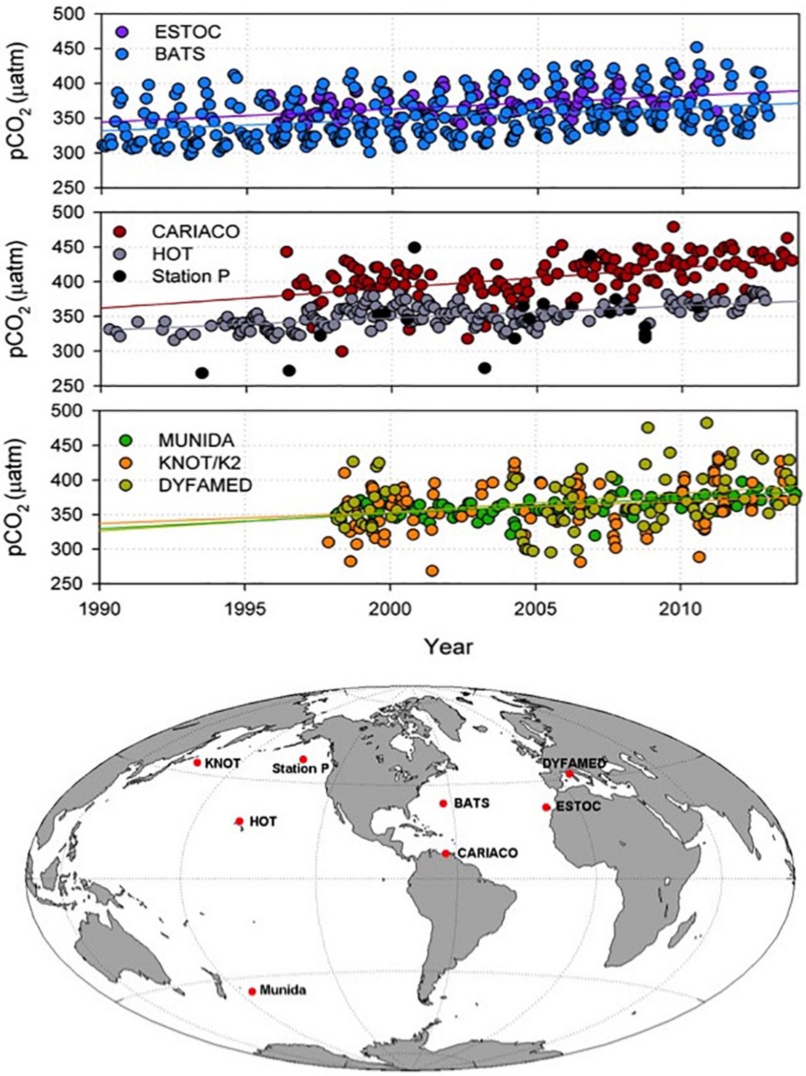

FIGURE 2 | Top: Time series observations of pCO_2 normalized for seasonal variations. **Bottom:** Locations of the time series stations. The increasing trend in pCO_2 observed over several decades at the time series stations is indicative of the increasing uptake of anthropogenic CO_2 by the ocean, which leads to rising ocean acidity. DYFAMED, DYnamique des Flux Atmosphériques en MEDiterranée; KNOT, Kyodo North west Pacific Ocean Time-series/K2. Figure modified from Tanhua et al. (2015).

Two to three decades of time series observations across the tropical and subtropical North Atlantic have recorded decadal-scale changes in the O_2 content of the subtropical underwater that are likely driven by ventilation changes tied to the Atlantic Multidecadal Oscillation (AMO) (Montes et al., 2016). The Candolim Time Series (CATS) off western India has documented an intensification of the O_2-deficient zone of the Arabian Sea, presumably in response to increases in land-derived nutrient inputs (Naqvi, 2006).

Biological Rates and Carbon Export

Long-term biogeochemical and ecological time series observations have yielded fundamental insights into processes controlling carbon exchange between the air and sea, rates of carbon transformation throughout the marine food web, and fluxes of carbon into the ocean's interior. For example, in subtropical gyres, annual net community production (NCP) and air–sea exchange of CO_2 dominate the flow of carbon near the ocean surface (Quay and Stutsman, 2003). NCP reflects the ocean's capacity to biologically sequester atmospheric CO_2 for periods of months to millennia by exporting organic carbon to the deep sea. Quantifying NCP with high confidence and reproducibility represents a key challenge for the oceanographic community. Ocean time series programs have provided seasonal observations for quantifying NCP by geochemical approaches (e.g., Neuer et al., 2007), and more recently have helped to facilitate development of a new suite of ocean productivity measurements that supplement shipboard observations with

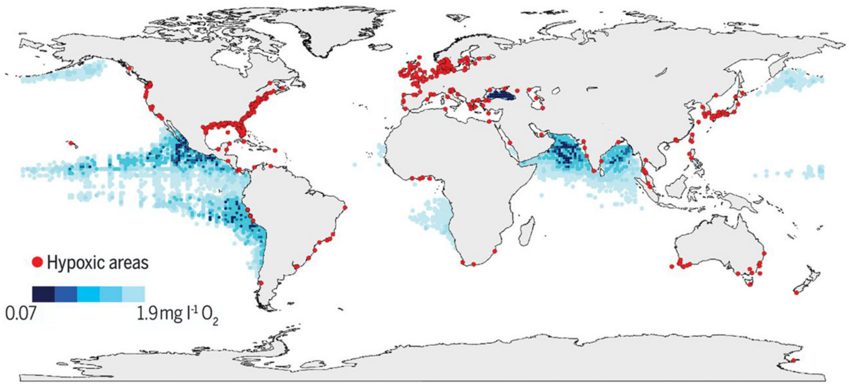

FIGURE 3 | Global map of low and declining O_2 levels in the open ocean and coastal waters from Breitburg et al. (2018). The global map indicates coastal sites where anthropogenic nutrients have exacerbated or caused O_2 declines to <2 mg L^{-1} (<63 μmol L^{-1}) (red dots), as well as ocean O_2 minimum zones at 300 m (blue shaded regions). Figure permissions granted through AAAS license # 4578800750164 (accompanying documentation provided).

autonomous and remote sensing platforms and sensors (Church et al., 2013). The use of new platforms for measurement of ocean NCP have broadened our understanding of the factors that drive changes in NCP over a range of space and time scales. As an example, measurements of upper ocean chemical mass balances of O_2 and dissolved inorganic carbon (DIC) made with a profiling float and a surface mooring at Ocean Station Papa have helped document the impact of the recent subarctic northeast Pacific warm sea surface temperature (SST) anomaly ("the Blob" – Bond et al., 2015) on annual NCP (Yang et al., 2018). Systematic comparison of different measurement- and platform-based NCP estimates is critical for identifying pathways that regulate carbon fluxes and testing assumptions and uncertainties underlying productivity measurements and models.

Marine Ecosystem Shifts and Species Distribution

Ocean time series observations have documented prominent marine ecosystem shifts associated with well known interannual- to decadal-scale climate cycles such as the El Niño-Southern Oscillation (ENSO) and the AMO. For example, in the coastal Pacific Ocean, ENSO has been shown to affect primary productivity in surface waters (IMARPE time series stations, Peru and MBARI, CA) (Chavez et al., 2011), while in the oligotrophic Pacific (HOT), a shift in the phytoplankton community was linked to changes in the North Pacific climate system (Karl et al., 2001; Corno et al., 2007). The CARIACO Ocean Time Series in the Cariaco Basin off the northern coast of Venezuela documented similarly important climate and ecosystem changes in the tropical Atlantic. In 2004, the phytoplankton community in this region underwent a marked shift from mostly diatoms to much smaller phytoplankton, accompanied by increased phytoplankton diversity and zooplankton biomass, and declining primary productivity. These changes reflected adjustments in regional circulation and biogeochemistry that were attributed to both natural shifts and human pressures, with severe negative impacts on local ecosystem services (Taylor et al., 2012). Regrettably, the CARIACO time series program was terminated in 2017.

Ocean time series have provided important insights regarding the impacts of anthropogenic change on individual species and communities of phytoplankton, which support the entire marine food web and are key players in global biogeochemical cycles. These data sets not only document ecological response but they provide the baseline knowledge needed to develop predictive capacity. Using historical data from the Continuous Plankton Recorder (CPR) time series in the North Atlantic, Barton et al. (2016) mapped the biogeography of prominent North Atlantic phytoplankton taxa and then used a model to project future changes in biogeography and community composition. While temperature is an important driver, this study also demonstrated the importance of ocean circulation and surface conditions that influence mixed layer depth (light, salinity, macronutrients). Similarly, an analysis of a long-term phytoplankton time series from the English Channel (Edwards et al., 2013) revealed highly predictable relationships between key functional traits easily measured in the laboratory (light utilization, nitrate uptake, growth rate) and seasonal environmental variations, providing the necessary basis for the use of trait-based modeling approaches to predict phytoplankton response to environmental change.

Management of Marine Resources

Ocean time series observations of marine ecosystems have the capacity to inform management of marine resources such as commercial fisheries and prediction of harmful algal blooms (HABs) and associated human health risks. Marine food webs are inextricably linked to human communities, particularly in coastal waters that are home to keystone commercial fisheries. Ocean time series observations off the United States east (Martha's Vineyard Coastal Observatory, MVCO) and west (CalCOFI) coasts have recently documented warming-related phenological changes in organisms at lower trophic levels. Such climate-driven shifts in bloom phenology affect the function of marine food webs and, ultimately, alter the ocean's capacity to provide food and sequester carbon. High-resolution flow cytometer measurements from

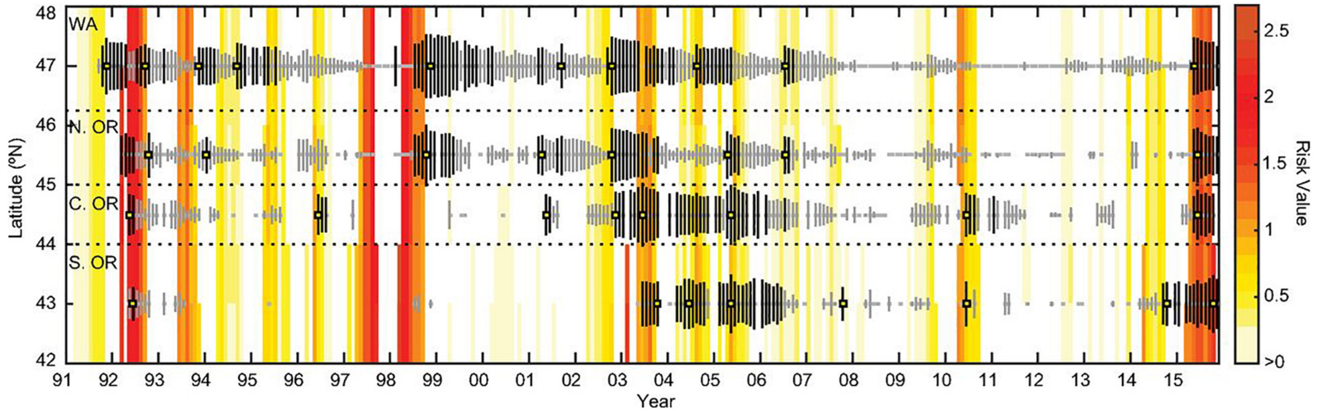

FIGURE 4 | Domoic Acid (DA) risk analysis model output (yellow to red) and DA levels in Oregon (OR) and Washington (WA) razor clams (vertical bars) from 1992 to 2015. Model values indicate increased risk of elevated DA based on proxies of warm ocean parameters; model values are only calculated during upwelling season, when concentrations of phytoplankton are likely to be greatest each year. White regions indicate that elevated DA is least likely, as the model equals zero and/or it is downwelling season. From top to bottom, monthly maximum DA values (vertical bars) are latitudinally binned as follows: WA (46.3°N to 48°N), northern OR (45°N to 46.3°N), central OR (44°N to 45°N), and southern OR (42°N to 44°N). Bar length is proportional to the monthly maximum DA value. Color indicates DA $\geq$ 20 ppm (black lines), from 1 to $<$ 20 ppm (gray lines), or not detected (gray squares). An absence of points indicates no DA data available. Annual DA maxima used in model evaluation are highlighted with yellow squares. Figure from McKibben et al. (2017).

an ocean time series in New England coastal waters revealed phenological changes in *Synechococcus*, with spring blooms occurring earlier in response to warmer water temperatures (Hunter-Cevera et al., 2016). Data from the CalCOFI time series (Asch, 2015) also showed shifts in the phenology of larval fishes tied to earlier surface ocean warming in the California Current ecosystem, a productive commercial fishery. A study from the northern California Current (McKibben et al., 2017) documented an increased incidence of shellfish containing domoic acid associated with warm SST anomalies during the upwelling season over the past 20 years. This warm water could be tied to the warm phases of the Pacific Decadal Oscillation (PDO) and ENSO. A risk assessment model based on this connection of climatic and local events can predict domoic acid outbreaks along the United States west coast and other eastern boundary current systems worldwide (**Figure 4**).

Challenges of Sustained Ocean Time Series Observations

Despite the well-established benefits of sustained marine ecosystem observations, ocean time series programs face many challenges, including:

- availability of sustained funding;
- varying levels of access to analytical facilities, instrumentation, and technology;
- lack of standardized sampling and analytical approaches across time series, all of which hinder comparability of data sets across sites (Lorenzoni and Benway, 2013);
- varying levels of data access with no community guidelines for data citation to ensure proper crediting of time series data providers (Neuer et al., 2017); and
- multiple disconnected databases and interfaces for accessing time series data without a universal set of data and metadata reporting guidelines.

In a funding environment that typically prioritizes innovative, curiosity-driven science and supports projects on 3- to 5-year timelines, it is a challenge to maintain long-term uninterrupted funding for ocean time series programs, which can result in data gaps, changes in sampling methodology and frequency, and high personnel turnover that can compromise data quality and scientific utility of the data sets. Additionally, long-term time series observations often rely on the availability of major infrastructure such as ships, which requires advance planning, scheduling, and attention to maintenance to support smooth operations. Thus, many time series operate on a shoestring budget or as add-ons to other existing sampling programs of opportunity, which are not necessarily sustainable. The fate of many time series programs is determined by the availability of resources and shifting priorities of public or private funding sources.

Data sharing and discoverability are still major issues in the ocean time series community. While some funding agencies require that time series data sets be made accessible to the broader community on a reasonable timeline, other time series data may have limited access with significant time lags or be fully proprietary, which presents a challenge to conducting science across time series sites. When a time series scientist's productivity is evaluated based on research and publications, there is limited incentive to invest time in sharing data that have been collected with a great deal of effort. Issues of time series data accessibility were recently broached via a survey of time series data contributors to the International Group for Marine Ecological Time Series (IGMETS) study, an effort led

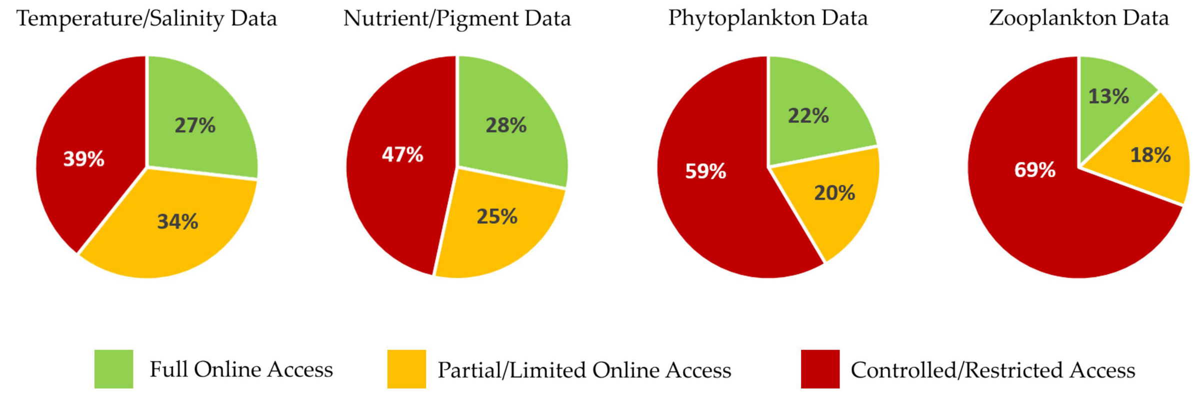

FIGURE 5 | Results of an anonymous survey sent out to all scientists who participated in the International Group for Marine Ecological Time Series (IGMETS) study indicating level of data accessibility by major variable groupings. Green indicates full/free online access to all of the data. Yellow/orange indicates that data are online but have intentional time delays of 2 years or subsetted/incomplete variable sets, requiring users to contact person/institute for the most up-to-date and complete data. Red indicates that none of the data are online and are only available by contacting the data collector or institutional data manager. Compared with physical and biogeochemical data, the percentage of freely available biological data is lower, with a relatively large fraction of zooplankton and phytoplankton data being protected. This likely reflects the amount of time and expertise that is required to collect biological data sets. Training a full species-level microscope plankton taxonomist takes years. Unrestricted and freely available plankton time series tend to be government-run programs with consistent funding that are often tied into legal mandates or water quality monitoring.

by the Intergovernmental Oceanographic Commission (IOC)-UNESCO, the International Ocean Carbon Coordination Project (IOCCP), and the Ocean Carbon and Biogeochemistry (OCB) Program (O'Brien et al., 2017). Based on survey responses (**Figure 5**), the top two reasons for limiting and/or delaying data access were: (1) to have sufficient time to QA/QC the data and research and publish new findings from their data collection efforts, and (2) to monitor community data usage as a means to justify continued support for the program(s). In addition, the oceanographic community has seen a proliferation of ocean databases with a broad range of overlapping scientific and programmatic drivers. Funding of these database-only initiatives not only takes away from support for oceanographic sampling efforts themselves (e.g., time series), but a continued lack of connectivity and interoperability among databases translates to a great deal of duplicative effort. The lack of synergy among databases also makes it more challenging for end-users to find comparable data sets of interest from within and across regions.

Addressing these issues will require a more unified and standardized approach for how time series data are managed and accessed in order to maximize the return on investment and enable ready access to end-users. Additionally, developing mechanisms to incentivize data sharing would go a long way toward addressing this problem. For example, collaborative time series science activities such as IGMETS and the International Council for the Exploration of the Sea (ICES) working groups on microbial, phytoplankton, and zooplankton ecology found that while many time series scientists were not willing to submit their data to a free-access public database, they were willing to loan their data to the working group's protected cooperative data pool to support comparative analysis and scientific products for broad distribution (Mackas et al., 2012; O'Brien et al., 2012, 2013, 2017; Paerl et al., 2015). This protected pool limits data access to working group participants and ensures that they receive proper citation, credit, and acknowledgment in any scientific product or paper that includes their data. While perhaps not an ideal solution, this model has been effective for supporting the development of topically focused scientific products that utilize time series data. These types of guarantees and controls are not typically available in a public database. IGMETS may have found an acceptable middle-ground, in which it will be creating a (optional-participation) data journal publication in conjunction with its next report, slated to be released in 2020. Data publications assign both a citation and a DOI to the contributed data, and have strong interest from the current IGMETS data-contributing participants. This concept has also been applied successfully for data submission to the Surface Ocean CO_2 Atlas (SOCAT). Ultimately, it is a high priority to identify solutions that reduce the lag time between data collection and provision, streamline data access, improve interoperability between data systems, and properly cite data providers.

OCEAN TIME SERIES OF THE FUTURE

Building Biological and Ecological Monitoring Capacity

Monitoring and diagnosing marine ecosystem change requires physiological and molecular measurements of individuals, as well as measurements at different ecosystem scales to explore changes in community structure, trophic dynamics, biodiversity, and biogeographic distribution. Currently, there is limited capacity to measure biological populations and processes remotely (autonomous and satellite-based platforms). Shipboard measurements and incubation experiments are constrained in their spatiotemporal representation, and there is still discrepancy across different methods and approaches, making it difficult to compare observations across multiple time series. While the oceanographic community has made great strides over the past couple of decades in developing physical and biogeochemical observing capacity, a more holistic understanding of marine ecosystem function and change is still needed. The oceanographic community is now developing sensors, instruments, platforms, and systems that could make large-scale and long-term ocean biological observation possible in the future. Advances in imaging, acoustic measurement, and genomic sensing show great promise for the future. Although each approach is in a different stage of maturity, there is great enthusiasm within the communities for investment to develop these capabilities. These observations of life in the sea complement and integrate with physical and biogeochemical observations, and together will provide a more comprehensive understanding of the ocean. Critical to this development is the involvement of private industry, and cooperative, fruitful partnerships between the scientific community and instrument developers to ensure that new technologies address observational needs in different oceanic regimes.

Shipboard and Autonomous Observations

A key scientific driver of many time series, particularly those from the JGOFS era, is the need to quantify the role of the ocean in the global carbon cycle, specifically the relationship between carbon export and biological productivity. Carbon export is frequently modeled as a function of primary production; however, analyses of primary production and export measurements from several ocean time series programs have revealed unexpected relationships between these processes (e.g., Helmke et al., 2010; Maiti et al., 2013). This may reflect methodological issues, undersampling of both production and export in time and space, and/or incomplete understanding of the pathways catalyzing carbon transformation through the oceanic food web. In many cases, time series programs have relied on the use of ^{14}C-bicarbonate assimilation as a proxy measurement of net primary production, with export derived from sediment trap estimates of sinking particle flux. Although both of these methodological approaches have received criticism, their consistent application at time series sites continues to provide insight into factors regulating temporal variability in upper ocean biology. More recently, measurements of NCP, including several approaches amenable to autonomous sensing, have been used with increasing frequency to further constrain productivity and carbon export. Among the most popular of these approaches are those leveraging high-frequency autonomous measurements of O_2 or bio-optical measurements of particle concentrations in the upper ocean (Juranek and Quay, 2013; Estapa et al., 2017). More routine integration of such measurements into existing time series programs will provide new insights into processes controlling time-varying relationships between productivity and export. Moreover, leveraging of such autonomous sensing methodologies with shipboard time series programs offers the potential for robust intercomparison across methods and new data to test our understanding of the connectivity between production and export.

Time-varying changes in plankton community structure are known to have direct influences on key ecosystem properties, including regulating the balance between productivity and respiration (i.e., NCP), governing rates of particulate matter export from the upper ocean to the interior waters, and altering the stoichiometry of nutrient availability and supply. State-of-the-art methodologies for assessing spatiotemporal dynamics in plankton biomass and community composition generally rely on: (1) microscopic visualization for quantification of plankton abundance, size, and diversity; (2) bio-optical characterization of plankton light harvesting pigments and/or estimates of bulk particulate material from absorption and scattering of light; and (3) nucleic acid- or protein-based analyses of plankton diversity, abundances, and metabolic function. Automated instruments that can enumerate and characterize individual plankton are an important class of technologies that have demonstrated capability to advance biological and ecological time series. In some cases, existing methodologies integrate one or more of these approaches; for example, development of an imaging flow cytometer couples the identification of plankton based on pigmentation to microscopic visualization of individual cells (Olson and Sosik, 2007; Sosik and Olson, 2007). Scanning flow cytometers (Dubelaar and Gerritzen, 2000), underway flow cytometers (Swalwell et al., 2011), and imaging-in-flow cytometers (Olson and Sosik, 2007) are now producing multi-month to multi-year time series of picocyanobacteria (Sosik et al., 2003; Hunter-Cevera et al., 2016), diatoms (Sosik and Olson, 2007; Peacock et al., 2014), dinoflagellates (Campbell et al., 2010, 2013; Dugenne et al., 2014), microzooplankton (Brownlee et al., 2016), and cytometrically defined subpopulations of phytoplankton (Thyssen et al., 2008). Notably, in many cases with these approaches, genus- to species-level resolution can be achieved, along with temporal resolution of hours to days. Time series capabilities have also been demonstrated for non-cytometric imaging instruments that are especially effective at characterizing relatively large colonial and chain-forming phytoplankton, mesozooplankton, marine snow, and other particles (e.g., Scripps Plankton Camera, Underwater Vision Profiler, Continuous Particle Imaging and Classification System, various holographic camera systems – e.g., Bochdansky et al., 2016). Such technologies are amenable to field-based deployment, permitting detailed spatiotemporal analyses of plankton community dynamics. While these technologies are providing unprecedented scales of observation, much of the focus has been on examining dynamics underlying stocks of plankton in the upper ocean. The development of new observational tools aimed at characterizing taxa that are actively contributing to export is needed to further elucidate linkages between plankton food webs and material and energy export.

Multi-frequency acoustic systems have more commonly been used in shipboard applications to help constrain distribution and biomass of zooplankton and fish but they can also be deployed via autonomous platforms (Benoit-Bird and Lawson, 2016), providing access to a broad range of spatial and temporal scales. Ship-based acoustic measurements have proven to be promising tools for estimating biomass and identifying small-scale physical features that affect nutrient availability and productivity (e.g., Lavery et al., 2010). Recent acoustic measurements of mesopelagic fish, which play a major role in marine food webs and carbon export, suggest that previous abundances have been significantly underestimated (Irigoien et al., 2014; Davison et al., 2015). More routine incorporation of acoustic technology across different platforms in ocean time series programs represents an important opportunity to monitor the health and status of marine ecosystems and their response to climate and environmental change, including ecological and biophysical interactions (Karstensen et al., 2015), animal physiology, biodiversity, biogeographic shifts, and contributions of different trophic levels to carbon export (Benoit-Bird and Lawson, 2016).

Several OceanObs'09 reviews (e.g., Borges et al., 2010; Byrne et al., 2010; Claustre et al., 2010) highlighted the need for new autonomous biogeochemical sensors and systems, in particular, sensors to quantify DIC and total alkalinity (TA). Either of these *in situ* systems, combined with available $p\mathrm{CO_2}$ or pH sensors, can be used to quantify the inorganic carbon system. These measurements, e.g., on a BATS mooring, could help understand the imbalance between NCP and export production, a longstanding conundrum that highlights the challenges of ship-based time series (Michaels et al., 1994), as discussed above. In fact, since OceanObs'09, new DIC and TA instruments have been successfully developed and their potential demonstrated with short deployments (Liu et al., 2013; Spaulding et al., 2014; Fassbender et al., 2015; Wang et al., 2015). These instruments are not widely used, however, because of their cost, complexity, power requirements, and reagent consumption. Slow but steady improvements are being made, but the timeline from initial concept to commercialization for *in situ* analyzers is typically $>$10 years. Public competitions such as the XPRIZE can provide the funding and community momentum needed to overcome such barriers and push the technology forward (e.g., Wendy Schmidt Ocean Health XPRIZE on pH sensor development to study ocean acidification, Okazaki et al., 2017). There is new technology similar to that used for O_2 optodes that could lead to simplified inorganic carbon sensors (Clarke et al., 2015, 2017). A variety of inexpensive and low-power infrared CO_2 sensors are also now being used for marine sensing applications (Fietzek et al., 2014; Bastviken et al., 2015; Hunt et al., 2017).

There has been a striking lack of sensor technologies able to overcome the challenges inherent in automated biological sampling in the ocean. As a result, these types of data sets have lagged behind those associated with physical, and to a certain extent, biogeochemical characterization. However, advances in recent years have poised the ocean observing community to overcome this challenge (e.g., Boss et al., 2018). Sophisticated autonomous bio-analytical systems have been developed that can characterize and quantify microbial populations through automated flow cytometry (Thyssen et al., 2014; Hunter-Cevera et al., 2016) and *in situ* genetic analysis (McQuillan and Robidart, 2017). These instruments have revealed unexpected diel microbial cycles (Ottesen et al., 2014) and provided new insight into the timing of spring blooms (Hunter-Cevera et al., 2016), as discussed above. Advances in *in situ* sampling and associated molecular-level characterization highlight another exciting path for future prospects that complement and extend other types of biological measurement capabilities. The Environmental Sample Processor (ESP; Scholin et al., 2017) is a noteworthy technological advance that has already provided time series observations with applications including quantification of biologically produced toxins (Doucette et al., 2009) and use of *in situ* hybridization to species-specific probes for sensitive detection of HAB species (Greenfield et al., 2006), zooplankton (Harvey et al., 2011), and bacteria (Robidart et al., 2012; Ussler et al., 2013). Emerging technologies and continuing developments promise to expand these applications and pave the way toward instrument systems that are smaller, require less power, and enable larger numbers of samples per deployment.

In the future, biogeochemistry and biological processes may be more intensively studied at time series sites by using multiple platforms, as is becoming commonplace in the physical oceanography community. For example, in the Salinity Processes in the Upper-ocean Regional Study (SPURS) (Lindstrom et al., 2017), sea surface salinity variability was studied by simultaneously using Eulerian (moorings) and Lagrangian (surface drifters, subsurface floats) platforms, 3-D mapping using surface and subsurface gliders and ships with a further broadscale view from satellites. Pioneering field programs such as EXport Processes in the Ocean from RemoTe Sensing (EXPORTS) (**Figure 6**) that extensively use *in situ* sensor technology centered on an established time series location (in this case Ocean Station Papa in the northeast Pacific Ocean), perhaps portend a multi-platform future for marine biogeochemical time series research.

Satellite Observations

To more effectively manage marine resources (e.g., fisheries, wetland systems, coral reef systems, etc.) and assess human health risks (e.g., HABs) in densely populated coastal regions, increased spatial and temporal resolution will be necessary. Remote sensing products have been fundamental tools for providing critical data in coastal regions and monitoring and understanding how marine ecosystems across the globe are responding to climate variability and change. Passive satellite ocean color measurements, as well as active remote sensing with Light Detection And Ranging (LiDAR), have proven to be essential for supporting science and applications related to ocean biogeochemistry and ecology. Remote sensing platforms provide some of the most fundamental global observations currently in existence, and the need for sustained space-based ocean observations has been highlighted at a global level [Schmitt, 2018; National Academies of Sciences, Engineering, and Medicine, 2017; Committee on Earth Observation Satellites (CEOS)].

In the coming decade, new advances in passive ocean color measurements such as the hyperspectral radiometer on the Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission will yield higher-resolution ocean color measurements that will enable diagnosis of key marine ecosystem parameters from space, such as phytoplankton community composition (Cetinić et al., 2018). Further development of active remote sensing tools such as LiDAR for ocean applications will provide critical information on the vertical distribution of plankton, and enable measurements in areas of high cloud cover or very high latitudes, where periods of winter darkness preclude complete annual

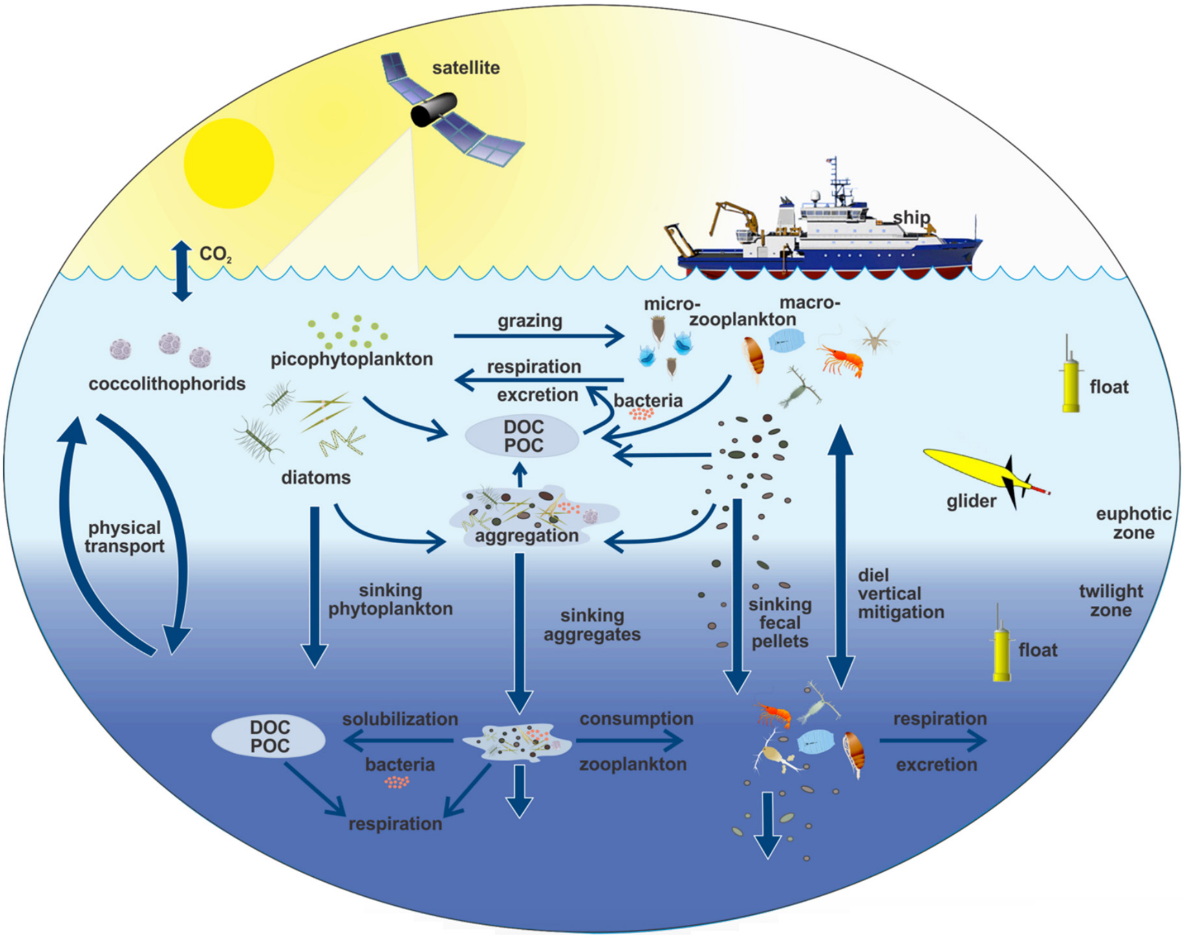

FIGURE 6 | Schematic of EXport Processes in the Ocean from Remote Sensing (EXPORTS) sampling campaign that includes ships, moorings, floats, gliders, sediment traps, and satellite observations. EXPORTS is a large-scale NASA-led field campaign that is leveraging existing ocean time series and other ocean observing assets to provide critical information for quantifying the export and fate of upper ocean net primary production (NPP) using satellite observations and state of the art ocean technologies. Figure from Siegel et al. (2016).

coverage of phytoplankton biomass (Behrenfeld et al., 2017). LiDAR systems remotely measure the vertical distributions of optical properties and particles in the upper ocean. Continued development of compact LiDAR systems for deployment on ships and autonomous platforms has the potential to greatly improve the quality and scope of a variety of oceanographic investigations, as demonstrated on recent deployments on passenger ferries as part of the Gulf of Maine North Atlantic Time Series (GNATS) program (Collister et al., 2018). More routine use of this technology will greatly improve our ability to investigate the role of particles in physical and biogeochemical oceanographic processes (see also Jamet et al., 2019).

Given the cost, infrastructure, and planning efforts involved, support for satellite missions typically happens at the national and international levels. With national science budgets either decreasing or remaining flat, it is essential that advocacy for ocean-focused, space-based missions remains high. International partnerships (e.g., CEOS) coupled with advancement of measurement technologies with planned missions remain at the forefront of all space agencies. Leveraging the rapidly growing small satellite and CubeSat industries will also be fundamental to advancing and expanding space-based ocean observations to better meet the measurement requirements needed to address scientific priorities. Over the past decade, small satellite and CubeSat instrumentation have seen a leap forward in technological development. These platforms will continue to expand over the next decade, increasing the potential for significant advancements in Earth system research through dramatically increased observational capabilities (e.g., Schueler and Holmes, 2016). In a review of the current state of the scientific and technological potential of CubeSats, the National Academies concluded that the technological innovation being developed through CubeSats has rendered access to space more affordable (National Academies of Sciences, Engineering, and Medicine, 2016); this in turn allows for the design of missions that could meet the observational requirements needed to study marine ecosystem structure and function, biogeochemical fluxes, phenology and biodiversity. CubeSats and small satellites also have the capacity to achieve higher spatial resolution (submesoscale) than standard satellite systems (Schueler and Holmes, 2016). CubeSat observations can complement observations from larger spacecrafts, increasing the scientific gains of a mission and establishing satellite constellations. As with any new technology, CubeSats and small satellites will require further testing and advancement to achieve climate-quality observations. Sensor performance, stability and reliability must be carefully evaluated prior to routine and widespread deployment of these platforms. Private industry and non-traditional vendors have interest in developing these technologies as well, and partnerships with scientists should be further explored and encouraged for the benefit of all.

Integration

Time series measurements made from different platforms (e.g., ships, autonomous platforms, and satellites) collectively provide the necessary spatiotemporal breadth required to monitor and study marine ecosystem function. When multiple time series are combined, a basin-wide and even global picture of variability can emerge. To better support science and management needs and fully realize the value of ocean time series programs, it is imperative that we invest in the development of numerical tools and approaches for bringing data sets together across different sites and platforms.

Data Integration

Large spatial-scale analyses using multiple time series enable the detection and interpretation of linkages between marine ecosystem function (e.g., food web dynamics, biogeochemistry, biodiversity, etc.) and climate variability and change (e.g., O'Brien et al., 2017). However, thus far, bringing together data sets across ocean time series in support of broader synthesis product development has met obstacles such as heterogeneity in sampling frequency and methodologies, as well as variable competing objectives and levels of data access across time series programs. While observations of physical parameters and associated data processing and quality control procedures are well established, biogeochemical parameters, particularly biological and ecological measurements, are less mature (Lindstrom et al., 2012). This represents a major frontier for data integration innovation across multidisciplinary time series sites, particularly shipboard platforms, that could initially focus on the most mature EOVs in order to achieve a higher degree of intercomparability. This is crucial for end-users who are interested in long-term marine changes such as ocean deoxygenation or ocean acidification that yield only small signal-to-noise ratios on shorter time scales. In addition, metadata reporting standards are lacking, particularly for novel technologies that are just now being integrated across time series (Lorenzoni and Benway, 2013).

An investment in data coordination across the time series community and with data management centers is needed to build a more sustainable and cost-effective data management model. Rather than investing in additional data management centers and portals, there is a much greater need for improved interoperability among existing centers that serve time series data. The community needs more opportunities (workshops, working groups, etc.) to work together to standardize data and metadata documentation and reporting protocols across platforms and variables to improve data discoverability and intercomparability. Data management centers and data portals also need improvement, as time series data formatting is often awkward, difficult to manipulate, and not standardized even within a single time series. Carefully curated data products with user-friendly interfaces and several different output formats would significantly improve usability of time series data.

Working Across Platforms

Targeted process studies and field campaigns have recently demonstrated great success using multi-platform measurements to study bloom dynamics (Fennel et al., 2011), carbon export (Cetinić et al., 2012; Omand et al., 2015; Siegel et al., 2016), and the role of mesoscale eddies in O_2 and nutrient availability (e.g., Mahadevan et al., 2012; Fiedler et al., 2016; Honda et al., 2018).

Autonomous sensors expand the observational footprint of ocean time series by capturing variability on shorter time scales. High-frequency measurements from stationary platforms such as moorings capture episodic events that contribute significantly to annual biogeochemical budgets and net ecosystem state (Jonsson and Salisbury, 2016). Platforms such as gliders can expand the observational footprint of a ship, providing the broader context needed to understand spatial variability in key marine ecosystem characteristics. Time series sites, especially those regularly accessed by ships, serve an important role both for sensor testing and the science conducted with sensors. Nearby oceanographic facilities and research vessels make it possible to deploy sensors on various platforms and recover after short periods (e.g., using gliders). For long-term deployments on moorings or free-drifting subsurface floats, shipboard time series can provide the necessary calibration data to quality-control and interpret the more limited sensor data (Johnson et al., 2010; Plant et al., 2016). For example, shipboard biogeochemical time series stations will play a critical role for groundtruthing data from emerging mobile autonomous observation networks such as the growing BGC-Argo program (Biogeochemical-Argo Planning Group, 2016).

Satellite observations provide the broader synoptic backdrop against which we can evaluate local and regional variability and trends (e.g., O'Brien et al., 2017). Among other services, sustained *in situ* time series serve a critical and necessary role in the vicarious calibration of satellite sensors and validation of remote sensing products. As remote sensing platforms have grown from a small number of satellites in the early years of ocean color observations (Barale and Schlittenhardt., 1993; Hooker et al., 1993) to the current international fleet of geostationary and Earth-orbiting ocean observing satellites, climate-quality *in situ* time series have become increasingly indispensable for calibration and validation of land, ocean, and atmospheric remote sensing products. Because satellites measure emitted and reflected radiation from the ocean surface as proxies for physical and biogeochemical parameters, *in situ* time series are critical in the development, testing, and refinement of remote sensing algorithms (e.g., Zibordi et al., 2015; Silsbe et al., 2016). As the next generation of satellite missions, including NASA's upcoming PACE mission and the Surface Biology and

Geology Designated Observable identified in the recent Decadal Survey for Earth Science (National Academies of Sciences, Engineering, and Medicine, 2018), push the boundaries of what is currently possible with remote sensing to support biological research from space, *in situ* time series will be even more critical for the development and validation of remote sensing algorithms and products.

Combining observations across platforms must become more routine and straightforward; this powerful multifocal approach for investigating the interplay between the different components of the ocean-atmosphere-climate system will yield improved understanding of the Earth system. Ocean measurements across scales are required to effectively identify large-scale marine ecosystem changes such as gyre expansion (Polovina et al., 2008) and changes in sea ice extent (Grebmeier et al., 2006), and evaluate their impacts on regional physics, biology, and biogeochemistry. Promoting and conducting multi-scale observations will also support improved forecasting and early warnings of public health threats such as HABs (Pitcher et al., 2010), changes in air quality, and evaluation of spatiotemporal distribution of pollutants, including aerosols and oil spills.

Time Series Network

Monitoring ocean change requires a sustained, globally distributed network of observatories that integrates shipboard, autonomous, and remote sensing platforms. There is tremendous value in community initiatives that combine data across sites, as they bring the ocean observing community together, working across individual time series programs, across nations, across disciplines, and across platforms to discuss and strategize effective solutions to challenges such as varied sampling intervals, data gaps, and developing common guidelines for data and metadata reporting. This also represents an important opportunity to build synergies among different observing networks and programs, and develop tools and numerical methods to facilitate more routine data integration.

A robust network of sustained ocean time series with common core sets of observations and compatible methodologies is essential for monitoring and understanding ecosystem-related changes. For example, OceanSITES is a global network of long-term, predominantly autonomous deepwater (open-ocean) reference stations measuring dozens of variables and monitoring the full depth of the ocean, from air-sea interactions down to 5,000 m. The mission of OceanSITES is to collect, deliver, and promote the use of high-quality data from long-term, high frequency observations at fixed locations in the open ocean. The global OceanSITES network (**Figure 7A**) is maintained by investigators from many countries that are collaborating to establish a global set of core oceanographic measurements being taken at OceanSITES stations. For historical reasons, this network has had a clear focus on physical parameters, but more recently, OceanSITES is starting to facilitate collection of biogeochemical measurements. Each of the moorings seeks its own support and schedules recovery and redeployment. If there was agreement among investigators on a common set of core observations and if a pool of instruments could be funded, provision of these instruments to site operators would initiate a core measurement program. An important precedent for this was when as part of the Deep Ocean Observing Strategy[1], OceanSITES took on the challenge of adding deep temperature (T)/salinity (S) time series to existing sites, raised funds to purchase a pool of deep T/S instruments, and now maintains a deep T/S observing array. Operators at many sites are willing to work with other investigators and programs to add sampling, as long as instruments meet mechanical and electrical requirements and do not compromise the existing mission of the mooring. For example, O_2 sensors have been added every other year to the Stratus surface mooring off northern Chile. Improved coordination between OceanSITES network sites and nearby or co-located shipboard time series programs (e.g., bottle samples to facilitate sensor calibration and testing) could greatly enhance the biogeochemical and biological measurement capacity of the OceanSITES network. An analogous global network does not formally exist for coastal ocean time series sites, where ecosystems typically experience a more dynamic range of variability and direct connections to, and impacts from, humans. In the United States, coordination through existing networks such as the National Association of Marine Laboratories (NAML) has been proposed as a means of developing a common scientific and logistical framework for monitoring and characterizing coastal marine ecosystems, informing management of marine resources, and providing ready access to engage and educate the public (Feller and Karl, 1996).

Fledgling efforts such as an international time series methods workshop in 2012 (Lorenzoni and Benway, 2013) provided the initial framework for a comparable global shipboard time series network that has since expanded via the work of IGMETS (O'Brien et al., 2017) to include >300 time series programs (**Figure 7B**). Despite their importance, several challenges have prevented shipboard time series from becoming a more formalized component of the GOOS. Shipboard data sets have primarily been used to support the goals of individual stations and ancillary projects, and apart from IGMETS, have thus far lacked a systematic effort aimed at regional to global data synthesis and development of continually updated products that are useful to the broader community, such as the Global Ocean Data Analysis Project (GLODAP) and the SOCAT. This represents an important opportunity and challenge for the ocean time series community in the coming decade. Developing a cohesive and vibrant international network of time series scientists will require high-level international coordination and leadership that is guided by a common set of objectives and a unifying framework for data collection, analysis, and reporting. This leadership body and the network that it supports will contribute to the cohesion of global time series platforms and the development of data products that address the needs of different end-users, and participate in regular activities that address key challenges such as standardizing methodological approaches to improve data intercomparability (e.g., Lorenzoni and Benway, 2013); streamlining time series data access and developing mechanisms to incentivize data sharing (e.g., DOI assignments

[1] http://www.deepoceanobserving.org/

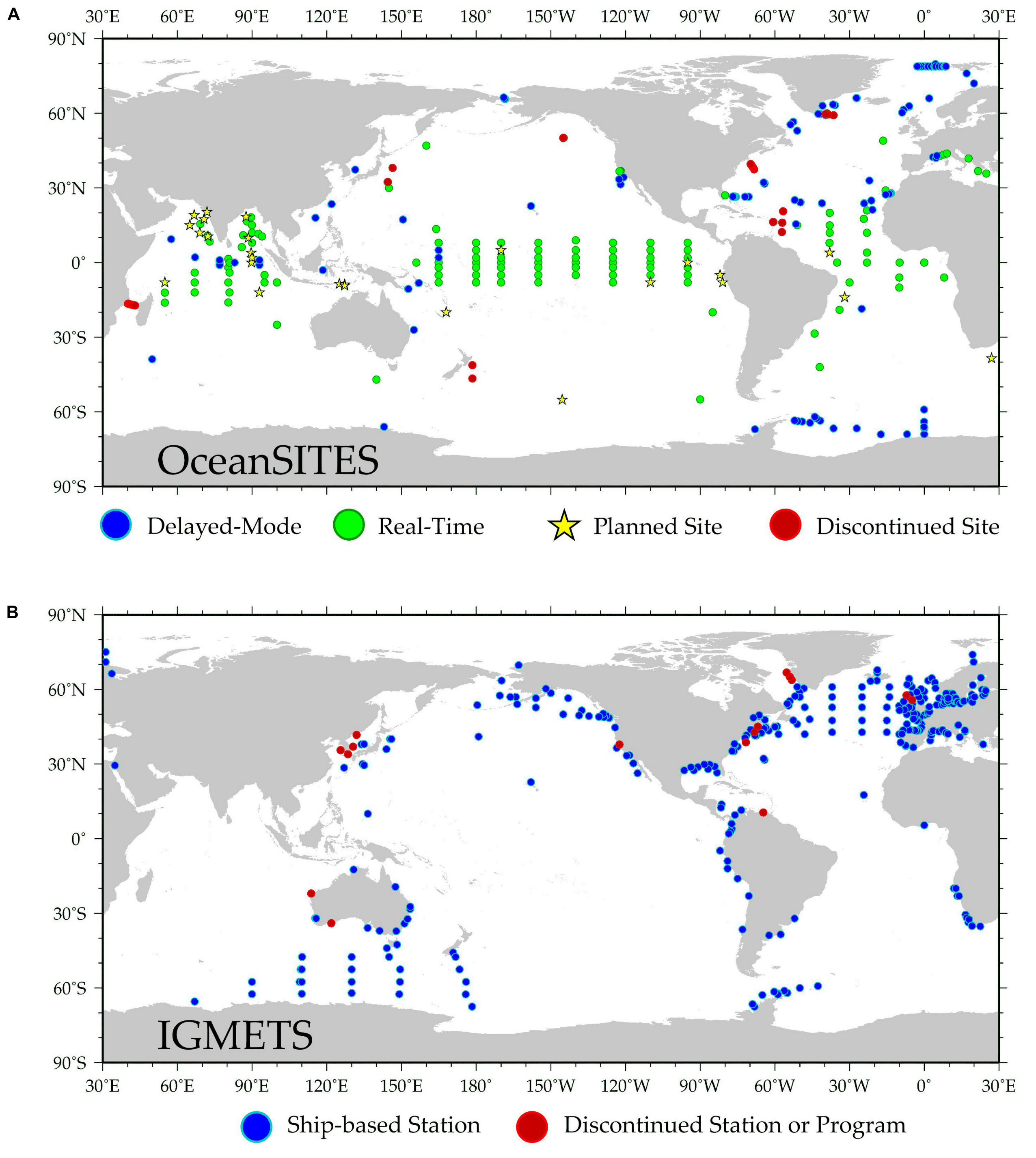

FIGURE 7 | (A) Map of predominantly autonomous ocean observing assets that make up the OceanSITES network (http://www.oceansites.org/). OceanSITES is a worldwide system of long-term, open-ocean reference stations measuring dozens of variables and monitoring the full depth of the ocean from air-sea interactions down to the seafloor. **(B)** Map of shipboard ocean time series programs that make up the IGMETS network (https://igmets.net/). IGMETS is an activity of IOC-UNESCO that seeks to integrate in situ biogeochemical variables from time series stations, together with satellite-derived information, to look at holistic changes within different ocean regions.

and data reports to increase citation of data sets); building partnerships with regional stakeholders to broaden the use of time series data sets; and increasing visibility and applicability of time series through advisory services, public outreach, and education (e.g., Milliman, 1996). Planning and investing in a regular (every 3–4 years) international time series community science workshop or symposium, perhaps comparable to the LTER Network's All Scientists' Meeting, to bring together time series scientists to share new results would greatly improve scientific exchange, collaboration, and coordination across time series programs.

Broadening the Ocean Time Series End-User Community

Ocean time series data currently serve a wide range of scientists studying ocean ecology, biogeochemical cycles, as well as physical and atmospheric dynamics. To bolster continued investment in these programs, we must broaden the community of time series data end-users. These sustained observations are highly valuable assets that enable important and often transformative discoveries and directly support applied research, advisory services (e.g., ecosystem-based management and policy), education, and technology development. Facilitating an ongoing dialogue with a broader end-user community and documenting outcomes of these exchanges is necessary to optimize the regional and global knowledge gained from sustained time series measurements. Strengthening ties to modelers, educators, and decision makers will form the basis for new networks and products to support capacity building, climate prediction, and policy, which will greatly increase the return on investment in these observing programs. To help refine and inform time series sampling efforts and identify opportunities for leveraging, add-ons, and product development, we need more effective mechanisms of collaborating and communicating with different time series data end-users. Ultimately, a robust network of sustained time series observations can be an effective avenue to facilitate collaborations between research and management communities.

Modelers and Time Series Data

Ecological processes are complex, and may involve time lags, environmental feedbacks, and complex interactions that are not easily discernible. Numerical models are important tools for synthesizing knowledge and generating and testing hypotheses, and, in particular, critical for disentangling complex dynamics and understanding large-scale processes such as energy budgets, carbon cycling, and ecosystem dynamics. Thus, it is important for time series data to be assimilated into modeling frameworks that may elucidate cause and effect scenarios not easily perceived through simple statistical analyses. Models can then be used to generate new hypotheses on underlying mechanisms, test the sensitivity of the system to perturbations, and make predictions of how a system might change in the future. In turn, time series measurements can become keystone observational datasets that enable modelers to assess the degree of confidence (or lack thereof) they have in their model's predictions. Indeed, models are only as good as the understanding and assumptions used to build them, and they require robust datasets to calibrate and validate model dynamics. As such, many models have relied on time series observations for validating the predicted dynamics in the model. Long-term time series provide a constraint on seasonal to decadal variability in physical, biological, and chemical parameters.

Yet, despite the apparent natural symbiosis between time series and models, several hurdles prevent widespread assimilation and use of time series data in models. Foremost are the challenges of measurement consistency across time series and data discovery. Different time series were started and have evolved to address specific regional ecosystem questions. Hence, there are discrepancies among core parameter sets being measured to study the forcings that drive regional ecosystem variability and long-term trends. Outside keystone time series such as HOT, CARIACO, and BATS, many modelers may be unaware of the range of observational programs producing time series data. Also, there is no standardization in the formatting of time series data such that post-processing (e.g., standardization and gridding) is required before models and data can be integrated. Often, formatting can change within a time series, making high-throughput post-processing challenging. Furthermore, there are often discontinuities such that some variables are not available throughout the duration of a time series. In the case of autonomous platforms such as moorings, data sets can be complicated by successive, unmerged mooring deployments; subsurface moorings that incline in response to currents, resulting in variable observing depths; disparate sampling rates among moored instruments, etc. Finally, sampling and measurement protocols are often not standardized between time series sites (or even over the historical period of a single site), and so time-consuming (and expensive) cross-site comparisons and validation may be necessary. In response to request from modelers, moored time series should be, where possible, merged into continuous, gap-free data with common sampling intervals. Clear documentation and metadata reporting should accompany time series data to provide clarity about how variables were measured – e.g., a variable as seemingly straightforward as SST may have different meanings for different communities and disciplines (skin temperature, temperature at 1 m on the surface buoy, bulk mixed layer temperature, etc.). Often, these challenges are tackled by individual research groups independently developing post-processing pipelines that may not be reproducible, robust or usable by others.

To facilitate increased use of time series data by the modeling community and improve communication and exchanges between observationalists and modelers, the use of shared repositories such as *GitHub* and services like *CodeOcean* can stimulate the development of community-driven, open source code for extracting, quality-controlling, and gridding time series data. Simply creating shared post-processing scripts that can be tailored for each individual modelers' needs will significantly decrease duplicative efforts, increase access to time series data, and ensure better validation of numerical models. Critically, experimentalists with expertise in observational methods, not numerical modelers, should be curating datasets prior to usage in models. Standardization across time series will also assist in the integration of time series data and models by creating intercomparable data products from many different regions of the globe. Finally, shared repositories will encourage the use of time series data for model validation, which will improve model quality. Targeted workshops that bring time series PIs and numerical modelers together would also be beneficial, in order to develop a system for setting up and sharing time series data. Such workshops could seed the development of communities centered on commonly used programming languages such as Python, MATLAB, and R. The activities would require modest effort and funding but have the potential to kickstart broader access to time series data that then could continue to grow organically. In addition, opening lines of communication will help support time series data managers to best serve the community by identifying issues with the current data portals. Connecting modelers who are accessing these datasets will build community and enhance knowledge sharing.

Supporting the Needs of Decision Makers

Sustained ocean time series data sets represent a unique opportunity to monitor marine ecosystem disturbances that directly affect human communities such as coastal and open ocean acidification, deoxygenation, HAB outbreaks, commercial fishery losses, and declining marine biodiversity. Indeed, monitoring and quantifying changes in marine ecosystems have already been important influences on policy at the local, national, and international levels. For example, the National Oceanic and Atmospheric Administration (NOAA) monitoring of fish stocks have been essential to the development of regional fisheries management policy in the United States (Methot, and Wetzel, 2013). Observations of pH and other carbon system parameters related to ocean acidification strongly influenced international policy deliberations of the International Maritime Organization (IMO) associated with injection of CO_2 into wells in the North Sea (Purdy, 2006). Mounting evidence of ocean warming emerging from Argo float observations was part of the rationale to establish the new United Nations (UN) Decade of Ocean Science for Sustainable Development (2021–2030).

As the oceans change and increasingly impact ecosystem services, information on biological and biogeochemical parameters will become more important in the future. A high priority is to facilitate expanded incorporation of marine ecological time series data into regional decision-making and policy-making. Biological observations of Marine Protected Areas (MPAs) have been called for as critical management tools for these relatively new features (Pomeroy et al., 2005). For example, management of California MPAs has required repeat measurement of the abundance of specific fish species (Gleason et al., 2010). Coastal managers are still working to identify key biological or biogeochemical variables that can be monitored to enable prediction of HABs, which are threats to human health and result in substantial losses in tourism revenues.

Initiating and sustaining a dialogue among time series scientists, stakeholders, and decision makers to co-generate knowledge and develop targeted products, activities, and visualization tools to inform decision-making is an essential first step in building lasting regional partnerships to address these challenges (e.g., Schubel, 1997; Dilling et al., 2006). To address emerging threats such as ocean acidification to coastal resources in the United States, several regional coastal acidification networks are fostering these important partnerships to plan and develop observing infrastructure and decision support products and tools. Thus far, these regional networks have served as an effective model for addressing targeted marine ecosystem threats such as acidification (e.g., Barton et al., 2015), warming, and hypoxia (e.g., Bograd et al., 2008).

As our ability to provide reliable biological and biogeochemical monitoring increases, we expect that the use of these measurements to expand understanding of how ecosystem services may be changing will increase. For example, rapid growth of open ocean aquaculture driven by demand for seafood protein will also result in increased need for monitoring the nearby waters, and as our use of ocean waters increases in the coming decades, the need for evaluation of our impact on the ocean will increase. As OceanObs'19 sets the stage for scientific and societal needs of ocean observations for the next decade, it is anticipated that the upcoming UN Decade of Ocean Science for Sustainable Development will further encourage the implementation of these recommendations and ensure that we have the scientific tools to evaluate those impacts.

Building Capacity Through Training and Education

Fostering a greater connection to and appreciation of the importance of the ocean in our daily lives (e.g., celebrations such as World Ocean Day) is an urgent priority to improve the scientific literacy of our public. Training opportunities and entities to help scientists more effectively communicate important findings to a broad audience will also help educate the public and inform decision-making.

Time series data sets support scientific inquiry from a range of end-users, including educators from grade schools and higher institutes of learning, as well as the general public. Despite the importance of education and outreach in raising public awareness and funding for time series programs, dedicated funding for outreach in particular is often minimal. This paradox (high payoff – low investment) necessitates strategic and creative approaches that leverage existing programs and networks and encourage open sharing and exchange of educational/outreach content to increase visibility of time series worldwide. For example, we must find new ways to educate and engage students (e.g., STEM-based curricula and modules to get classrooms working with time series data streams) and the general public (e.g., content development for informal learning centers, radio interviews, newspapers, and other popular media). For example, regularly sharing the current state of atmospheric (e.g., Keeling curve) and oceanic CO_2 in social and print media can help raise public awareness about this problem and simultaneously highlight the importance of sustained observations for monitoring and addressing the problem. Autonomous programs such as Argo and OOI provide near real-time data streams that can be readily incorporated into classroom curricula and even serve as the basis for courses in data management, data visualization, and ocean sciences in general.

Hosting immersive open house experiences for schools, media, and other formal and informal education centers would provide a firsthand look at the importance of sustained repeat observations for monitoring the state of our planet. Typically, very few citizens will have stepped onto an oceanographic research vessel, touched or handled ocean research equipment such as floats and gliders (or even a CTD), or seen plankton through a microscope. These experiences can be illuminating, if not transformative, for many. Some time series programs already have extensive outreach programs that include classroom activities, outreach workshops, and online tools to engage users of all ages. Seagoing programs provide a natural platform for experiential learning at the undergraduate and graduate levels. They generate contextual data for research and an interdisciplinary scope that can broaden a student's knowledge base. Shipboard platforms are also increasingly incorporating teacher-at-sea programs, virtual classrooms, blogs, and social media to engage the public in these shared investments.

Several established ocean time series sites around the globe possess both the technical infrastructure and scientific expertise to facilitate the necessary training, capacity building, and technology transfer to build a truly global time series network. Ongoing initiatives such as the Nippon Foundation – POGO Alumni Network for Oceans (NANO) represent important opportunities to build capacity and support collaboration, education, and communication across the international ocean sciences community. Global distribution of shipboard biogeochemical time series sites shows major gaps in less developed parts of the world such as Africa. This is not only caused by reduced financial and technical resources in these regions, but also by a lack of human capacity. A training program such as the POGO-led Ocean Training Partnership could be expanded to include ocean time series programs and provide scientists from less developed countries access to shipboard biogeochemical time series sites, where they could actively participate and gain expertise via a Training-Through-Research approach (TTR). This would foster an expansion of a truly global ocean time series network that is inclusive of both developed and developing nations. Routine exchange programs across time series enable scientists of all career stages to engage in important intercomparison activities (calibration, methodological testing, development and testing of standards and reference materials, etc.), share knowledge, and develop new collaborations.

Expanding and investing in initiatives that go beyond individual training to build communities of practice is a high priority requiring partnerships that extend beyond scientific funding entities. Indeed, time series are multidisciplinary programs, so access to training, capacity building, and outreach opportunities must extend beyond traditional oceanographic disciplines. Engaging groups such as statisticians, mathematicians, data librarians, programmers, etc. brings critical expertise to the table that lays the foundation for time series data analysis, synthesis, and product development to expand the reach of time series programs and benefit the community-at-large.

Data Products to Support Science and Society

In order for shipboard biogeochemical time series sites to become an operational component of GOOS, well-defined protocols for uniform data processing and flow need to be developed. This is an essential step in closing the value chain and making these data more routinely available to a broader set of end-users, including stakeholders and decision makers. For instance, time series sites with their high-temporal-resolution data sets could provide annual updates on the state of local-regional marine ecosystems and associated biogeochemical processes affecting the global oceans (e.g., ocean deoxygenation, acidification). Such a mechanism would greatly enhance the visibility of individual sites and also help achieve the United Nations (UN) Sustainable Development Goal (SDG) target 14.3 "minimize and address the impacts of ocean acidification." Another example hails from the international voluntary observing ship (VOS) network, which has developed the data synthesis product SOCAT (Bakker et al., 2016). This data synthesis product is being updated annually with the most recent quality-controlled data, made immediately available for international end-users. Subsequently, these data are being integrated into the calculation of a global carbon budget (Le Quéré et al., 2018). The Global Carbon Project (GCP) releases the budget on an annual basis and communicates the scientific results up to the policymaker level.

The shipboard biogeochemical time series network holds the scientific capacity to also report on the state of global biogeochemical processes (e.g., a marine "Keeling" curve for the global oceans). For example, IGMETS investigators have synthesized data and analyzed trends in *in situ* biogeochemical variables from >300 globally distributed time series stations. Together with satellite-derived ocean temperature and chlorophyll, the objective of the first IGMETS study (O'Brien et al., 2017) was to identify holistic changes in marine ecosystems within different ocean regions over the past one to three decades, to explore plausible connections at a global level, and to highlight regions of the ocean that are undergoing especially large biogeochemical and ecological changes. With the development of basic time series data interfaces and explorers that enabled the visualization of trends over different time periods (**Figure 8**), the first IGMETS study just scratched the surface of what is possible for time series synthesis products. The next IGMETS study, due out in 2020, will continue to improve these tools and data fields, and engage the modeling community with the aim of producing a data journal publication featuring the data of participating time series.

While the oceanographic community has made great strides over the past couple of decades integrating measurements across platforms, there are still challenges in bringing data together, calling for the development of consistent methodologies and data reporting guidelines. There is a lack of a dedicated data synthesis mechanism and dedicated funding to support these efforts. Developing such a data synthesis product does not require us to start from scratch. A substantial amount of data infrastructure has already been developed under several SOCAT iterations, and protocols exist for handling shipboard biogeochemical data under the GLODAP. However, major tasks are: (1) to develop quality control protocols that are tailored to fixed-point biogeochemical time series sites in order to ensure best possible intercomparability across sites; and (2) to secure resources for such an effort.

It is fundamental that time series data be used for more than just scientific inquiry and research. As time series bridge the gap between science and society, and scientific information from these platforms flows to managers and policy makers in a more transparent manner, more tuned applications and research

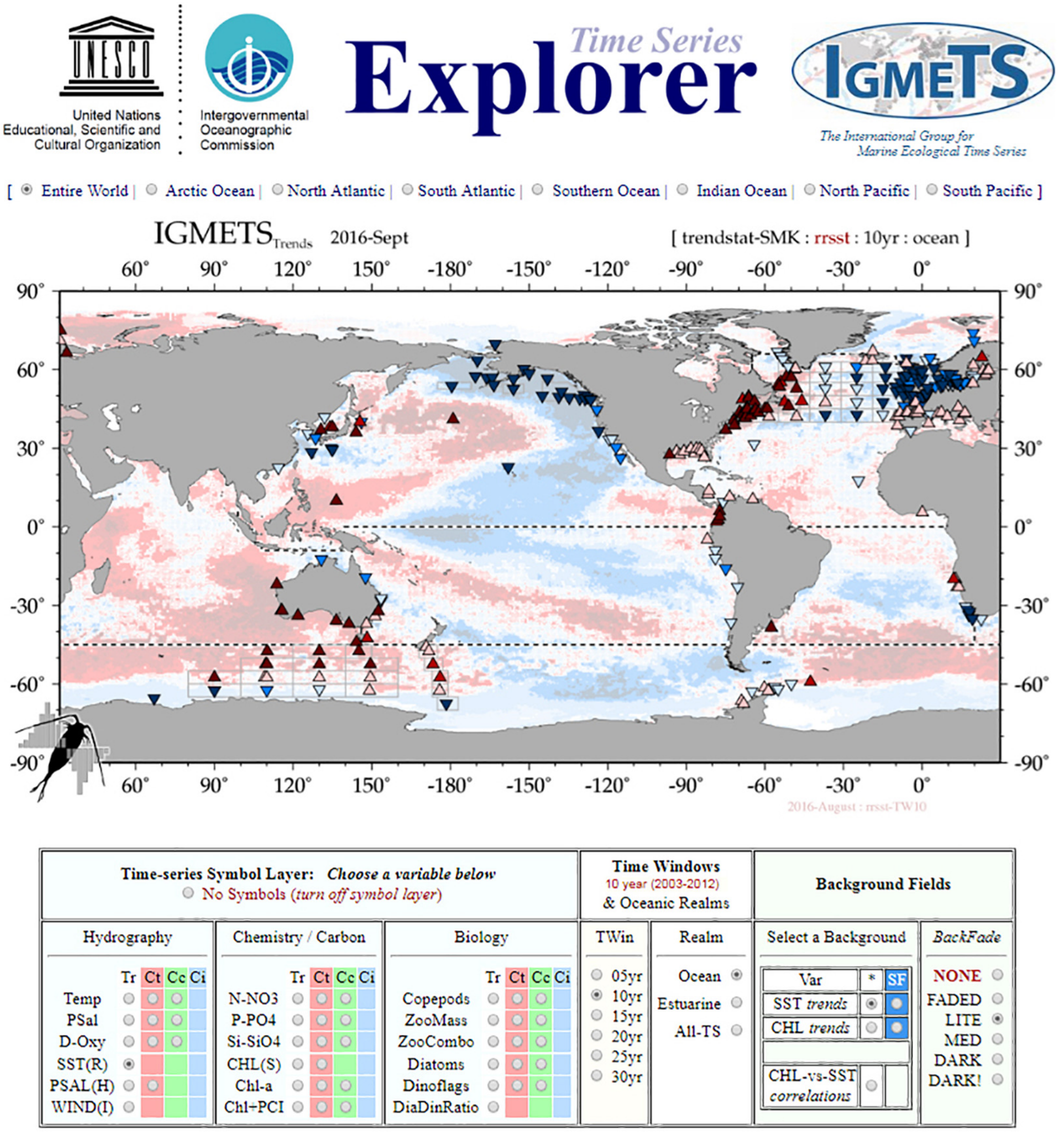

FIGURE 8 | Product highlights from the first International Group for Marine Ecological Time Series (IGMETS) study (O'Brien et al., 2017), which split the time series into the Explorer, which illustrates trends in different variables over time, and the Metabase, an interactive time series information and discovery tool. The next generation of IGMETS will combine Explorer and Metabase into a single tool that enables the user to find time series and preview their variables, trends, and background fields using a single interface rather than having to switch between two different systems.

questions geared toward society will be able to emerge. These "fit-for-purpose" time series data products will not only be able to inform specific decision making, but will also help ensure support for basic research conducted by the time series.

SUMMARY AND ACTIONABLE RECOMMENDATIONS

The ocean is a prominent fixture of our global economy and our global health, providing a range of services to society, the first and foremost of which is food security. More than 3 billion people currently rely on the ocean as their primary protein source (UN SDG 14). IPCC findings have clearly documented climate-driven changes in ocean temperature, chemistry, phenology, and biogeographic distributions of organisms, which will have lasting effects on marine ecosystems (Pörtner et al., 2014). In a time of accelerating changes, sustained repeat measurements from ocean time series will become an even more fundamental component of our GOOS, since these data sets represent the most effective means available to characterize marine ecosystem shifts and explore causal links and implications for human communities. Ocean time series have withstood many challenges, and over the past decade, at least half a dozen ship-based time series, some older than a decade or more, have been discontinued due to a lack of funding or personnel. The fate of many time series programs

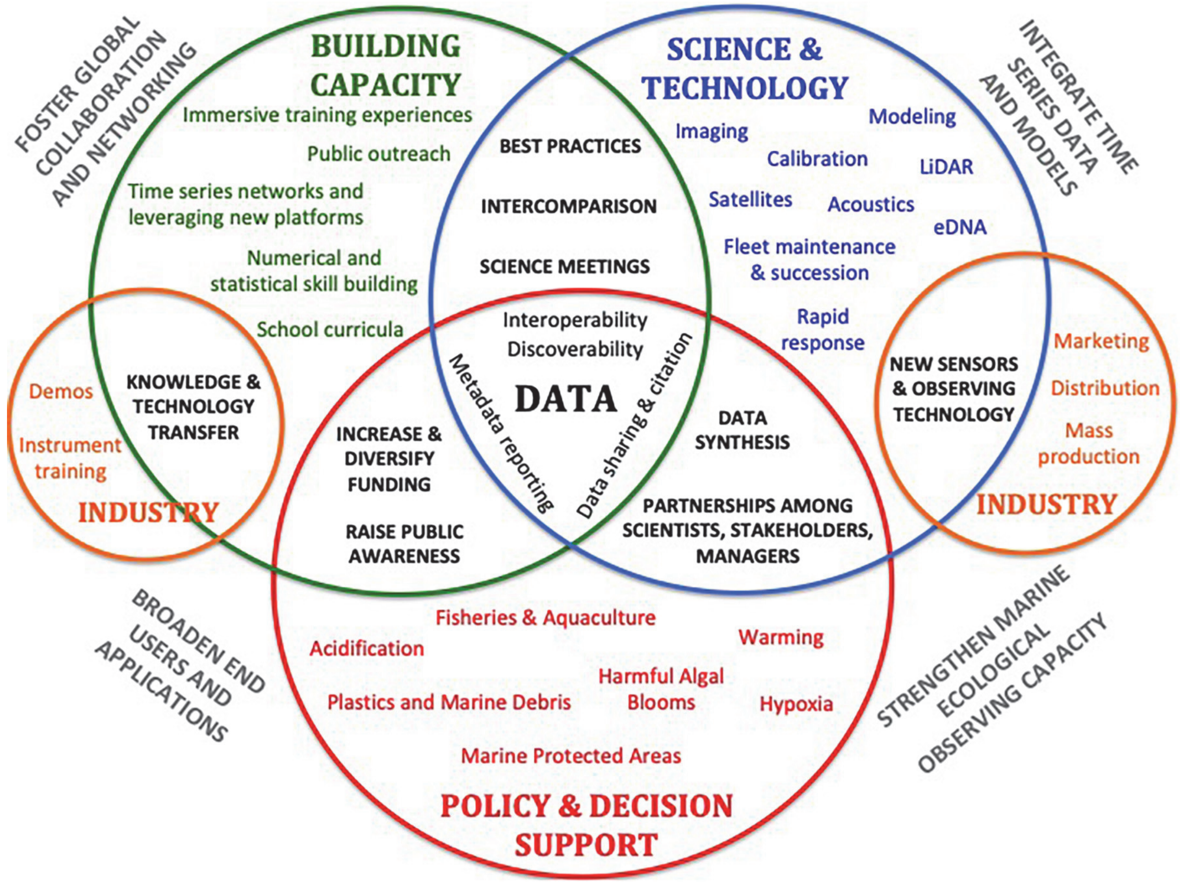

FIGURE 9 | Venn diagram illustration of proposed themes and implementation mechanisms for marine ecological time series of the future.

is subject to availability of resources, and shifting priorities of public funding sources endangers their sustainability. Developing partnerships with the private sector, philanthropic foundations, local and state governments, NGOs, and other groups offers the potential to diversify time series funding sources and more effectively engage interested stakeholders (Baker et al., 2019).

Effective monitoring of marine ecosystems requires sustained regional networks of physical, biological, and biogeochemical time series observations that integrate shipboard, autonomous, and remote sensing platforms. In order to effectively address the challenges before us, we propose a new vision (**Figure 9**) for the coordination, collection, synthesis, and broader applications of ocean time series measurements that includes the following components:

(1) Strengthen marine ecological observing capacity through enhancement of shipboard, autonomous, and satellite-based observing assets.
   - Leverage platforms of opportunity (e.g., container ships, fishing vessels, etc.) and augment existing observing infrastructure and arrays with new biogeochemical and biological measurements.
   - Incorporate existing and emerging technology to enhance time series programs, including plankton and particle imaging systems; automated flow cytometry, *in situ* genetic sample collection and analysis (eDNA); shipboard and autonomous acoustic and LiDAR systems; new inorganic CO_2 system sensors; and satellite-based passive and active technology such as multispectral and hyperspectral radiometers (e.g., NASA PACE), space-based LiDARs, and CubeSats.
   - Work across shipboard, autonomous, and satellite platforms to maximize opportunities for calibration, validation, sensor testing, and algorithm development.
   - Develop new biological sensor technology (beyond fluorescence, scattering, etc.).
   - Enhance capacity (available observing assets, funding) to deploy individual time series programs and ocean observing system (-OOS) networks for adaptive, rapid-response sampling of anomalous ocean/climate events (blooms, marine heat waves, etc.).

(2) Promote greater integration of time series data and models to better understand processes underlying ocean change and improve predictive capacity.
   - Establish repositories for modelers to share code for extracting and gridding time series data to avoid duplicative effort.

- Coordinate activities to increase dialogue between time series data generators and modelers to build capacity (programming languages, data analysis, numerical methods, etc.) and streamline data access and processing.

(3) Broaden applications and end-users of time series data.
- Build partnerships (networks, publications, proposals, etc.) among scientists, managers, and stakeholders to utilize ocean time series observations in monitoring and managing ocean challenges like acidification, warming, fisheries decline, HABs, etc. and assessing efficacy of management approaches.
- Incorporate time series data into educational modules and curricula, informal learning exhibits, and popular media outlets to instill the value of sustained long-term marine ecosystem monitoring.
- Use time series platforms to provide immersive oceanographic learning and research experiences for students, educators, and the public.
- Invest in training opportunities (e.g., Ocean Training Partnership) to transfer knowledge and facilitate collaboration across career stages and between developed and developing nations.
- Establish standardized data processing protocols to support use of time series data in products that can inform decision-making (e.g., ecosystem health indices, gridded synthesis products, local/regional/global trend visualizers, etc.).

(4) Foster global collaboration and networking to advance science, expand and improve measurements, and optimize data access.
- Identify mechanisms to incentivize data sharing and credit data providers (e.g., protected data pools, DOI assignments, etc.).
- Standardize data and metadata reporting protocols for different platforms and variables.
- Regularly assess and compare methodologies within and across time series (e.g., Lorenzoni and Benway, 2013).
- Improve data discoverability and interoperability across data centers and portals and support more flexible output formats to serve a broader range of applications and end-users.
- Bring together members of the international time series community on a regular basis to share scientific findings (e.g., "all-scientist meetings," special sessions at international meetings, etc.).
- Build numerical and statistical capacity through courses, tutorials, etc. for working with large multi-platform data streams.

AUTHOR CONTRIBUTIONS

HB and LL provided vision and leadership in the conceptualization and writing of this manuscript. All authors contributed sections of the text, as well as editing, feedback, and discussion throughout the development of this manuscript.

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REFERENCES

Asch, R. (2015). Climate change and decadal shifts in the phenology of larval fishes in the California Current ecosystem. *Proc. Natl. Acad. Sci. U.S.A.* 112, 4065–4074. doi: 10.1073/pnas.1421946112

Baker, D. J., Glackin, M., Roberts, S., Schmitt, R. W., Twigg, E., Vimont, D., et al. (2019). The challenge of sustained ocean observations. *Front. Mar. Sci.* 6:105. doi: 10.3389/fmars.2019.00105

Bakker, D. C. E., Pfeil, B., Landa, C. S., Metzl, N., O'Brien, K. M., and Olsen, A. (2016). A multi-decade record of high-quality $f CO_2$ data in version 3 of the Surface Ocean CO_2 Atlas (SOCAT). *Earth Syst. Sci. Data* 8, 383–413. doi: 10.5194/essd-8-383-2016

Barale, V., and Schlittenhardt, P. M. (eds). (1993). *Ocean Colour: Theory and Applications in a Decade of CZCS Experience*. Dordrecht: Kluwer Acadamic, 367

Barton, A., Waldbusser, G. G., Feely, R. A., Weisberg, S. B., Newton, J. A., and Hales, B. (2015). Impacts of coastal acidification on the Pacific Northwest shellfish industry and adaptation strategies implemented in response. *Oceanography* 28, 146–159. doi: 10.5670/oceanog.2015.38

Barton, A. D., Irwin, A. J., Finkel, Z. V., and Stock, C. A. (2016). Anthropogenic climate change drives shift and shuffle in North Atlantic phytoplankton communities. *Proc. Natl. Acad. Sci. U.S.A.* 113, 2964–2969. doi: 10.1073/pnas.1519080113

Bastviken, D., Sundgren, I., Natchimuthu, S., Reyier, H., and Gålfalk, M. (2015). Technical note: cost-efficient approaches to measure carbon dioxide (CO_2) fluxes and concentrations in terrestrial and aquatic environments using mini loggers. *Biogeosciences* 12, 3849–3859. doi: 10.5194/bg-12-3849-2015

Bates, N. R., Astor, Y. M., Church, M. J., Currie, K., Dore, J. E., and González-Dávila, M. (2014). A time series view of changing ocean chemistry due to ocean uptake of anthropogenic CO_2 and ocean acidification. *Oceanography* 27, 126–141. doi: 10.5670/oceanog.2014.16

Behrenfeld, M. J., Hu, Y., O'Malley, R. T., Boss, E. S., Hostetler, C. A., and Siegel, D. A. (2017). Annual boom-bust cycles of polar phytoplankton biomass revealed by space-based lidar. *Nat. Geosci.* 10, 118–122. doi: 10.1038/ngeo2861

Benoit-Bird, K. J., and Lawson, G. L. (2016). Ecological insights from pelagic habitats acquired using active acoustic techniques. *Ann. Rev. Mar. Sci* 8, 463–490. doi: 10.1146/annurev-marine-122414-034001

Biogeochemical-Argo Planning Group (2016). *The Scientific Rationale, Design and Implementation Plan for a Biogeochemical-Argo Float Array*. Issy-les-Moulineaux: Ifremer.

Bochdansky, A. B., Clouse, M. A., and Herndl, G. J. (2016). Dragon kings of the deep sea: marine particles deviate markedly from the common number-size spectrum. *Sci. Rep.* 6:22633. doi: 10.1038/srep22633

Bograd, S. J., Castro, C. G., Di Lorenzo, E., Palacios, D. M., Bailey, H., Gilly, W., et al. (2008). Oxygen declines and the shoaling of the hypoxic boundary in the California Current. *Geophys. Res. Lett.* 35:L12607. doi: 10.1029/2008GL034185

Bond, N. A., Cronin, M. F., and Freeland, H. (2015). The Blob: an extreme warm anomaly in the northeast Pacific. In state of the climate in 2014 global oceans. *Bull. Am. Meteorol. Soc.* 96, S62–S63.

Borges, A., Alin, S., Chavez, F., Vlahos, P., Johnson, K., Holt, J., et al. (2010). "A global sea surface carbon observing system: inorganic and organic carbon dynamics in coastal oceans," in *Proceedings of the OceanObs'09: Sustained Ocean Observations and Information for Society*, Vol. 2, eds J. Hall, D. E. Harrison, and D. Stammer (Venice: ESA Publication), 21–25. doi: 10.5270/OceanObs09.cwp.07

Boss, E., Waite, A., Muller-Karger, F., Yamazaki, H., Wanninkhof, R., and Sosik, H. (2018). Beyond chlorophyll fluorescence: the time is right to expand biological measurements in ocean observing programs. *Limnol. Oceanogr. Bull.* 27, 89–90. doi: 10.1002/lob.10243

Breitburg, D., Levin, L. A., Oschlies, A., Gregoire, M., Chavez, F. P., and Conley, D. J. (2018). Declining oxygen in the global ocean and coastal waters. *Science* 359:eaam7240. doi: 10.1126/science.aam7240

Brownlee, E. F., Olson, R. J., and Sosik, H. M. (2016). Microzooplankton community structure investigated with imaging flow cytometry and automated live-cell staining. *Mar. Ecol. Prog. Ser.* 550, 65–81. doi: 10.3354/meps11687

Byrne, R., DeGrandpre, M., Short, R., Martz, T., Merlivat, L., and McNeil, C. (2010). "Sensors and systems for in situ observations of marine carbon dioxide system variables," in *Proceedings of the OceanObs'09: Sustained Ocean Observations and Information for Society*, Vol. 2, eds J. Hall, D. E. Harrison, and D. Stammer (Venice: ESA Publication), 21–25. doi: 10.5270/OceanObs09.cwp.13

Campbell, L., Henrichs, D. W., Olson, R. J., and Sosik, H. M. (2013). Continuous automated imaging-in-flow cytometry for detection and early warning of Karenia brevis blooms in the Gulf of Mexico. *Environ. Sci. Pollut. Res.* 20, 6896–6902. doi: 10.1007/s11356-012-1437-4

Campbell, L., Olson, R. J., Sosik, H. M., Abraham, A., Henrichs, D. W., and Hyatt, C. J. (2010). First harmful *Dinophysis* (Dinophyceae, Dinophysiales) bloom in the U.S is revealed by automated imaging flow cytometry. *J. Phycol.* 46, 66–75. doi: 10.1111/j.1529-8817.2009.00791.x

Cetinić, I., McClain, C. R., and Werdell, P. J. (2018). *Pre-aerosol, Clouds, and ocean Ecosystem (PACE) Mission Science Definition Team Report*. NASA PACE Technical Report Series vol. 2. Washington, DC: NASA.

Cetinić, I., Perry, M. J., Briggs, N. T., Kallin, E., D'Asaro, E. A., and Lee, C. M. (2012). Particulate organic carbon and inherent optical properties during 2008 North Atlantic Bloom Experiment. *J. Geophys. Res* 117:C06028. doi: 10.1029/2011JC007771

Chavez, F. P., Messié, M., and Pennington, J. T. (2011). Marine primary production in relation to climate variability and change. *Ann. Rev. Mar. Sci.* 2011. 3, 227–260. doi: 10.1146/annurev.marine.010908.163917

Church, M. J., Lomas, M. W., and Muller-Karger, F. (2013). Sea change: charting the course for biogeochemical ocean time-series research in a new millennium. *Deep Sea Res. Part 2 Top. Stud. Oceanogr.* 93, 2–15. doi: 10.1016/j.dsr2.2013.01.035

Clarke, J. S., Achterberg, E. P., Connelly, D. P., Schuster, U., and Mowlem, M. (2017). Developments in marine pCO_2 measurement technology; towards sustained in situ observations. *Trends Anal. Chem.* 88, 53–61. doi: 10.1016/j.trac.2016.12.008

Clarke, J. S., Achterberg, E. P., Rérolle, V. M. C., Abi Kaed Bey, S., Floquet, C. F. A., and Mowlem, M. C. (2015). Characterisation and deployment of an immobilised pH sensor spot towards surface ocean pH measurements. *Anal. Chim. Acta* 897, 69–80. doi: 10.1016/j.aca.2015.09.026

Claustre, H., Bishop, J., Boss, E., Stewart, B., Berthon, J. F., and Coatanoan, C. (2010). "Bio-Optical profiling floats as new observational tools for biogeochemical and ecosystem studies: potential synergies with ocean color remote sensing," in *Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society*, Vol. 2, eds J. Hall, D. E. Harrison, and D. Stammer (Venice: ESA Publication), 21–25. doi: 10.5270/OceanObs09.cwp.17

Collister, B. L., Zimmerman, R. C., Sukenik, C. I., Hill, V. J., and Balch, W. M. (2018). Remote sensing of optical characteristics and particle distributions of the upper ocean using shipboard lidar. *Remote Sens. Environ.* 215, 85–96. doi: 10.1016/j.rse.2018.05.032

Corno, G., Karl, D. M., Church, M. J., Letelier, R. M., Lukas, R., Bidigare, R. R., et al. (2007). Impact of climate forcing on ecosystem processes in the North Pacific Subtropical Gyre. *J. Geophys. Res.* 112:C04021. doi: 10.1029/2006JC003730

Davison, P. C., Koslow, J. A., and Kloser, R. J. (2015). Acoustic biomass estimation of mesopelagic fish: backscattering from individuals, populations, and communities. *ICES J. Mar. Sci.* 72, 1413–1424. doi: 10.1093/icesjms/fsv023

Dilling, L., Mitchell, R., Fairman, D., Lahsen, M., Mohser, S., and Patt, A. (2006). "How can we improve the usefulness of carbon science for decision-making," in *Proceedings of the First State of the Carbon Cycle Report (SOCCR): The North American Carbon Budget and Implications for the Global Carbon Cycle Climate Change Science Program CCSP Product* 2.2, Washington, DC.

Doucette, G. J., Mikulski, C. M., Jones, K. L., King, K. L., Greenfield, D. I., Marin, R., et al. (2009). Remote, subsurface detection of the algal toxin domoic acid onboard the Environmental Sample Processor: assay development and initial field trials. *Harmful Algae* 8, 880–888. doi: 10.1016/j.hal.2009.04.006

Dubelaar, G., and Gerritzen, P. (2000). CytoBuoy: a step forward towards using flow cytometry in operational oceanography. *Sci. Mar.* 64, 255–265. doi: 10.3989/scimar.2000.64n2255

Dugenne, M., Thyssen, M., Nerini, D., Mante, C., Poggiale, J.-C., and Garcia, N. (2014). Consequence of a sudden wind event on the dynamics of a coastal phytoplankton community: an insight into specific population growth rates using a single cell high frequency approach. *Front. Microbiol.* 5:485. doi: 10.3389/fmicb.2014.00485

Edwards, K. F., Litchman, E., and Klausmeier, C. A. (2013). Functional traits explain phytoplankton community structure and seasonal dynamics in a marine ecosystem. *Ecol. Lett.* 16, 56–63. doi: 10.1111/ele.12012

Estapa, M., Durkin, C., Buesseler, K., Johnson, R., and Feen, M. (2017). Carbon flux from bio-optical profiling floats: calibrating transmissometers for use as optical sediment traps. *Deep Sea Res. Part 1 Oceanogr. Res. Papers* 120, 100–111. doi: 10.1016/j.dsr.2016.12.003

Fassbender, A. J., Sabine, C. L., Lawrence-Slavas, N., De Carlo, E. H., Meinig, C., and Maenner Jones, S. (2015). Robust sensor for extended autonomous measurements of surface ocean dissolved inorganic carbon. *Environ. Sci. Technol.* 49, 3628–3635. doi: 10.1021/es5047183

Feller, R. J., and Karl, D. M. (1996). The National Association of Marine Laboratories: a connected web for studying long-term changes in U.S. coastal and marine waters. *Biol. Bull.* 190, 269–277. doi: 10.2307/1542549

Fennel, K., Cetinić, I., D'Asaro, E., Lee, C., and Perry, M. J. (2011). Autonomous data describe North Atlantic spring bloom. *Eos Trans. AGU* 92:465. doi: 10.1029/2011eo500002

Fiedler, B., Grundle, D. S., Schütte, F., Karstensen, J., Löscher, C. R., and Hauss, H. (2016). Oxygen utilization and downward carbon flux in an oxygen-depleted eddy in the eastern tropical North Atlantic. *Biogeosciences* 13, 5633–5647. doi: 10.5194/bg-13-5633-2016

Fietzek, P., Fiedler, B., Steinhoff, T., and Körtzinger, A. (2014). In situ quality assessment of a novel underwater pCO_2 sensor based on membrane equilibration and NDIR Spectrometry. *J. Atmos. Ocean. Technol.* 31, 181–196. doi: 10.1175/JTECH-D-13-00083.1

Gleason, M., McCreary, S., Miller-Henson, M., Ugoretz, J., Fox, E., and Merrifield, M. (2010). Science-based and stakeholder-driven marine protected area network planning: a successful case study from north central California. *Ocean Coast. Manag.* 53, 52–68. doi: 10.1016/j.ocecoaman.2009.12.001

Grebmeier, J. M., Overland, J. E., Moore, S. E., Farley, E. V., Carmack, E. C., and Cooper, L. W. (2006). A major ecosystem shift in the northern Bering Sea. *Science* 311, 1461–1464. doi: 10.1126/science.1121365

Greenfield, D. I., Marin, R. III, Jensen, S., Massion, E., Roman, B., and Feldman, J. (2006). Application of the Environmental Sample Processor (ESP) methodology for quantifying *Pseudo-nitzschia australis* using ribosomal RNA-targeted probes in sandwich and fluorescent in situ hybridization. *Limnol. Oceanogr. Methods* 4, 426–435. doi: 10.4319/lom.2006.4.426

Gruber, N., Clement, D., Carter, B. R., Feely, R. A., van Heuven, S., and Hoppema, M. (2019). The oceanic sink for anthropogenic CO_2 from 1994 to 2007. *Science* 363, 1193–1199. doi: 10.1126/science.aau5153

Harvey, J. B. J., Ryan, J. P., Marin, R. III, Preston, C., Alvarado, N., Scholin, C. A., et al. (2011). Robotic sampling, in situ monitoring, and molecular detection of marine zooplankton. *J. Exp. Mar. Biol. Ecol.* 413, 60–70. doi: 10.1016/j.jembe.2011.11.02

Helmke, P., Neuer, S., Lomas, M. W., Conte, M., and Freudenthal, T. (2010). Cross-basin differences in particulate organic carbon export and flux attenuation in the subtropical North Atlantic gyre. *Deep Sea Res. Part 1* 57, 213–227. doi: 10.1016/j.dsr.2009.11.001

Henson, S. A., Beaulieu, C., and Lampitt, R. (2016). Observing climate change trends in ocean biogeochemistry: when and where. *Glob. Change Biol.* 22, 1561–1571. doi: 10.1111/gcb.13152

Honda, M. C., Sasai, Y., Siswanto, E., Kuwano-Yoshida, A., Aiki, H., and Cronin, M. F. (2018). Impact of cyclonic eddies and typhoons on biogeochemistry in the oligotrophic ocean based on biogeochemical/physical/meteorological time series at station KEO. *Prog. Earth Planet. Sci.* 5:42. doi: 10.1186/s40645-018-0196-193

Hooker, S. B., McClain, C. R., and Holmes, A. (1993). Ocean color imaging: CZCS to SeaWiFS. *MTS J.* 27, 3–15.

Hunt, C. W., Snyder, L., Salisbury, J. E., Vandemark, D., and McDowell, W. H. (2017). SIPCO2: a simple, inexpensive surface water pCO_2 sensor. *Limnol. Oceanogr. Methods* 15, 291–301. doi: 10.1002/lom3.10157

Hunter-Cevera, K. R., Neubert, M. G., Olson, R. J., Solow, A. R., Shalapyonok, A., and Sosik, H. M. (2016). Physiological and ecological drivers of early spring blooms of a coastal phytoplankter. *Science* 354, 326–329. doi: 10.1126/science.aaf8536

Irigoien, X., Klevjer, T. A., Røstad, A., Martinez, U., Boyra, G., Acuña, J. L., et al. (2014). Large mesopelagic fishes biomass and trophic efficiency in the open ocean. *Nat. Commun.* 5:3271. doi: 10.1038/ncomms4271

Jamet, C., Ibrahim, A., Ahmad, Z., Angelini, F., Babin, M., Behrenfeld, M. J., et al. (2019). Going beyond standard ocean color observations: polarimetry and LiDAR. *Front. Mar. Sci.* 6:251. doi: 10.3389/fmars.2019.00251

Johnson, K. S., Riser, S. C., and Karl, D. M. (2010). Nitrate supply from deep to near-surface waters of the North Pacific subtropical gyre. *Nature* 465, 1062–1065. doi: 10.1038/nature09170

Jonsson, B. F., and Salisbury, J. E. (2016). Episodicity in phytoplankton dynamics in a coastal region. *Geophys. Res. Lett.* 43, 5821–5828. doi: 10.1002/2016GL068683

Juranek, L. W., and Quay, P. D. (2013). Using triple isotopes of dissolved oxygen to evaluate global primary productivity. *Ann. Rev. Mar. Sci.* 5, 503–524. doi: 10.1146/annurev-marine-121211-172430

Karl, D. M. (2010). Oceanic ecosystem time series programs: ten lessons learned. *Oceanography* 23, 104–125. doi: 10.5670/oceanog.2010.27

Karl, D. M., Bates, N. R., Emerson, S., Harrison, P. J., Jeandal, C., and Llinas, O. (2003). "Temporal studies of biogeochemical processes determined from ocean time series obsevations during the JGOFS era," in *Ocean Biogeochemistry: The Role of the Ocean Carbon Cycle in Global Change*, ed. M. J. R. Fasham (New York, NY: Springer), 239–267. doi: 10.1007/978-3-642-55844-3_11

Karl, D. M., Bidigare, R., and Letelier, R. (2001). Long-term changes in plankton community structure and productivity in the North Pacific Subtropical Gyre: the domain shift hypothesis. *Deep Sea Res. Part 2 Top. Stud. Oceanogr.* 48, 1449–1470. doi: 10.1016/S0967-0645(00)00149-141

Karstensen, J., Fiedler, B., Schütte, F., Brandt, P., Körtzinger, A., and Fischer, G. (2015). Open ocean dead zones in the tropical North Atlantic Ocean. *Biogeosciences* 12, 2597–2605. doi: 10.5194/bg-12-2597-2015

Lampitt, R. S., Favali, P., Barnes, C. R., Church, M. J., Cronin, M. F., and Hill, K. L. (2010). "In situ sustained Eulerian observatories," in *Proceedings of the OceanObs09: Sustained Ocean Observations and Information for Society*, Vol. 1, eds J. Hall, D. E. Harrison, and D. Stammer (Venice: ESA Publication), 21–25. doi: 10.5270/OceanObs09.pp.27

Lavery, A. C., Chu, D., and Moum, J. N. (2010). Measurements of acoustic scattering from zooplankton and oceanic microstructure using a broadband echosounder. *ICES J. Mar. Sci.* 67, 379–394. doi: 10.1093/icesjms/fsp242

Le Quéré, C., Andrew, R. M., Friedlingstein, P., Sitch, S., Pongratz, J., Manning, A. C., et al. (2018). Global Carbon Budget 2017. *Earth Syst. Sci. Data* 10:2018. doi: 10.5194/essd-10-405-2018

Lindstrom, E., Gunn, J., Fischer, A., McCurdy, L. K., and Glover, A. (2012). *A Framework for Ocean Observing. IOC Information Document*. Paris: *UNESCO*, doi: 10.5270/OceanObs09-FOO

Lindstrom, E. J., Shcherbina, A. Y., Rainville, L., Farrar, J. T., Centurioni, L. R., and Dong, S. (2017). Autonomous multi-platform observations during the Salinity Processes in the Upper-ocean Regional Study. *Oceanography* 30, 38–48. doi: 10.5670/oceanog.2017.218

Liu, X., Byrne, R. H., Adornato, L., Yates, K. K., Kaltenbacher, E., Ding, X., et al. (2013). In situ spectrophotometric measurement of dissolved inorganic carbon in seawater. *Environ. Sci. Technol.* 2013, 11106–11114. doi: 10.1021/es4014807

Lorenzoni, L., and Benway, H. M. (eds). (2013). "Report of Global intercomparability in a changing ocean," in *Proceedings of the international time series methods workshop, 2012, Ocean Carbon and Biogeochemistry (OCB) Program and International Ocean Carbon Coordination Project (IOCCP)*, (St. George's: Bermuda Institute of Ocean Sciences), 61.

Mackas, D. L., Pepin, P., and Verheye, H. (2012). Interannual variability of marine zooplankton and their environments: within- and between-region comparisons. *Prog. Oceanogr.* 97–100, 1–14. doi: 10.1016/j.pocean.2011.11.002

Mahadevan, A., D'Asaro, E., Lee, C., and Perry, M. J. (2012). Eddy-driven stratification initiates North Atlantic spring phytoplankton blooms. *Science* 337, 54–58. doi: 10.1126/science.1218740

Maiti, K., Charette, M. A., Buesseler, K. O., and Kahru, M. (2013). An inverse relationship between production and export efficiency in the Southern Ocean. *Geophys. Res. Lett.* 40, 1557–1561. doi: 10.1002/grl.50219

McKibben, S. M., Peterson, W., Wood, A. M., Trainer, V. L., Hunter, M., and White, A. E. (2017). Climatic regulation of the neurotoxin domoic acid. *Proc. Nat. Acad. Sci.* 114, 239–244. doi: 10.1073/pnas.1606798114

McQuillan, J. S., and Robidart, J. C. (2017). Molecular-biological sensing in aquatic environments: recent developments and emerging capabilities. *Curr. Opin. Bio Technol.* 45, 43–50. doi: 10.1016/j.copbio.2016.11.022

Methot, R. D. Jr., and Wetzel, C. R. (2013). Stock synthesis: a biological and statistical framework for fish stock assessment and fishery management. *Fish. Res.* 142, 86–99. doi: 10.1016/j.fishres.2012.10.012

Michaels, A. F., Bates, N. R., Buesseler, K. O., Carlson, C. A., and Knap, A. H. (1994). Carbon-cycle imbalances in the Sargasso Sea. *Nature* 372, 537–540. doi: 10.1038/372537a0

Milliman, J. D. (1996). Integrating research and education with public outreach at coastal laboratories. *Biol. Bull.* 190, 278–285. doi: 10.2307/1542550

Montes, E., Muller-Karger, F. E., Lorenzoni, L., Cianca, A., Lomas, M., and Habtes, S. (2016). Decadal variability in the oxygen inventory of North Atlantic subtropical underwater captured by sustained, long-term oceanographic time series observations. *Glob. Biogeochem. Cycles* 30, 460–478. doi: 10.1002/2015GB005183

Naqvi, S. W. A. (2006). Oxygen deficiency in the north Indian Ocean. *Gayana* 70(Suppl.1), 53–58. doi: 10.4067/S0717-65382006000300011

National Academies of Sciences, Engineering, and Medicine (2016). *Achieving Science with CubeSats: Thinking Inside the Box*. Washington, DC: The National Academies Press, doi: 10.17226/23503

National Academies of Sciences, Engineering, and Medicine (2017). *Sustaining Ocean Observations to Understand Future Changes in Earth's Climate*. Washington, DC: The National Academies Press, doi: 10.17226/24919

National Academies of Sciences, Engineering, and Medicine (2018). *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space*. Washington, DC: The National Academies Press, doi: 10.17226/24938

Neuer, S., Benway, H., Bates, N., Carlson, C., Church, M., and DeGrandpre, M. (2017). Monitoring ocean change in the 21st Century. *Eos* 98, doi: 10.1029/2017EO080045

Neuer, S., Cianca, A., Helmke, P., Freudenthal, T., Davenport, R., and Meggers, H. (2007). Biogeochemistry and hydrography in the eastern subtropical North Atlantic gyre: results from the European time-series station ESTOC. *Prog. Oceanogr.* 72, 1–29. doi: 10.1016/j.pocean.2006.08.001

O'Brien, T. D., Li, W. K. W., and Morán, X. A. G. (eds). (2012). *ICES Phytoplankton and Microbial Plankton Status Report* 2009/2010. ICES Cooperative Research Report No. 313. Copenhagen: ICES, 196.

O'Brien, T. D., Lorenzoni, L., Isensee, K., and Valdés, L. (eds). (2017). *What are Marine Ecological Time Series telling us about the ocean?* A status report. IOC-UNESCO, IOC Technical Series, No. 129: 297. Paris: IOC-UNESCO.

O'Brien, T. D., Wiebe, P. H., and Falkenhaug, T. (eds). (2013). *ICES Zooplankton Status Report 2010/2011.* ICES Cooperative Research Report No. 318. Copenhagen: ICES, 208.

Okazaki, R. R., Sutton, A. J., Feely, R. A., Dickson, A. G., Alin, S. R., Sabine, C. L., et al. (2017). Evaluation of marine pH sensors under controlled and natural

conditions for the Wendy Schmidt ocean health XPRIZE. *Limnol. Oceanogr. Methods* 15, 586–600. doi: 10.1002/lom3.10189
Olson, R. M., and Sosik, H. M. (2007). A submersible imaging-in-flow instrument to analyze nano- and microplankton: imaging FlowCytobot. *Limnol. Oceanogr. Methods* 5, 195–203. doi: 10.4319/lom.2007.5.195
Omand, M. M., D'Asaro, E. A., Lee, C. M., Perry, M. J., Briggs, N., Cetinić, I., et al. (2015). Eddy-driven subduction exports particulate organic carbon from the spring bloom. *Science* 348, 222–225. doi: 10.1126/science.1260062
Ottesen, E. A., Young, C. R., Gifford, S. M., Eppley, J. M., Marin, R., and Schuster, S. C. (2014). Multispecies diel transcriptional oscillations in open ocean heterotrophic bacterial assemblages. *Science* 345:207. doi: 10.1126/science.1252476
Paerl, H. W., Yin, K., and O'Brien, T. D. (2015). SCOR Working Group 137: "Global Patterns of Phytoplankton Dynamics in Coastal Ecosystems": an introduction to the special issue of Estuarine, Coastal and Shelf Science. *Estuarine Coast. Shelf Sci.* 162, 1–3. doi: 10.1016/j.ecss.2015.07.011
Peacock, E. E., Olson, R. J., and Sosik, H. M. (2014). Parasitic infection of the diatom *Guinardia delicatula*, a recurrent and ecologically important phenomenon on the New England Shelf. *Mar. Ecol. Prog. Ser.* 503, 1–10. doi: 10.3354/meps10784
Pitcher, G. C., Jiménez, A. B., Kudela, R. M., and Reguera, B. (2010). Harmful algal blooms in eastern boundary upwelling systems. *Oceanography* 30, 22–35. doi: 10.5670/oceanog.2017.107
Plant, J. R., Johnson, K. S., Sakamoto, C. M., Jannasch, H. W., Coletti, L. J., and Riser, S. C. (2016). Net community production at Ocean Station Papa observed with nitrate and oxygen sensors on profiling floats. *Glob. Biogeochem. Cycles* 30, 859–879. doi: 10.1002/2015gb005349
Polovina, J. J., Howell, E. A., and Abecassis, M. (2008). Ocean's least productive waters are expanding. *Geophys. Res. Lett* 35:L03618. doi: 10.1029/2007GL031745
Pomeroy, R. S., Cid, G. A., Parks, J. E., and Watson, L. M. (2005). How is your MPA doing? A methodology for evaluating the management effectiveness of marine protected areas. *Ocean Coast. Manag.* 48, 485–502. doi: 10.1016/j.ocecoaman.2005.05.004
Pörtner, H.-O., Karl, D. M., Boyd, P. W., Cheung, W. W. L., Lluch-Cota, S. E., and Nojiri, Y. (2014). "Ocean systems," in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, et al. (Cambridge: Cambridge University Press), 411–484.
Purdy, R. (2006). The legal implications of carbon capture and storage under the sea. *Sustainable Dev.Law Policy* 7, 22–26.
Quay, P., and Stutsman, J. (2003). Surface layer carbon budget for the subtropical N. Pacific: $\delta^{13}C$ constraints at station ALOHA. *Deep Sea Res. Part 1* 50, 1045–1061. doi: 10.1016/S0967-0637(03)00116-X
Robidart, J. C., Preston, C. M., Paerl, R. W., Turk, K. A., Mosier, A. C., and Francis, C. A. (2012). Seasonal dynamics of *Synechococcus* and *Thaumarchaeal* microbial populations in Monterey Bay resolved in real time with remote in situ instrumentation. *ISME J.* 6, 513–523. doi: 10.1038/ismej.2011.127
Sabine, C. L., Feely, R. A., Gruber, N., Key, R. M., Lee, K., and Bullister, J. L. (2004). The oceanic sink for anthropogenic CO_2. *Science* 305, 367–371. doi: 10.1126/science.1097403
Schmitt, R. W. (2018). The ocean's role in climate. *Oceanography* 31, 32–40. doi: 10.5670/oceanog.2018.225
Scholin, C. A., Birch, J., Jensen, S., Marin, R. III, Massion, E., and Pargett, D. (2017). The quest to develop ecogenomic sensors: a 25-year history of the Environmental Sample Processor (ESP) as a case study. *Oceanography* 30, 100–113. doi: 10.5670/oceanog.2017.427
Schubel, J. R. (1997). Observations on science and management. *Amer. Zool.* 37, 563–574.
Schueler, C., and Holmes, A. (2016). Hawkeye: CubeSat SeaWiFS update. *Proc. SPIE* 9978, doi: 10.1117/12.2237374
Siegel, D. A., Buesseler, K. O., Behrenfeld, M. J., Benitez-Nelson, C. R., Boss, E., Brzezinski, M. A., et al. (2016). Prediction of the export and fate of global ocean net primary production: the exports science plan. *Front. Mar. Sci.* 3:22. doi: 10.3389/fmars.2016.00022
Silsbe, G. M., Behrenfeld, M. J., Halsey, K. H., Milligan, A. J., and Westberry, T. K. (2016). The CAFE model: a net production model for global ocean phytoplankton. *Glob. Biogeochem. Cycles* 30, 1756–1777. doi: 10.1002/2016gb005521
Sosik, H. M., and Olson, R. J. (2007). Automated taxonomic classification of phytoplankton sampled with imaging-in-flow cytometry. *Limnol. Oceanogr. Methods* 5, 204–216. doi: 10.4319/lom.2007.5.204
Sosik, H. M., Olson, R. J., Neubert, M. G., Shalapyonok, A., and Solow, A. R. (2003). Growth rates of coastal phytoplankton from time series measurements with a submersible flow cytometer. *Limnol. Oceanogr.* 48, 1756–1765. . doi: 10.4319/lo.2003.48.5.1756
Spaulding, R. S., DeGrandpre, M. D., Beck, J. C., Hart, R. D., Peterson, B., and DeCarlo, E. H. (2014). Autonomous in situ measurements of seawater alkalinity. *Env. Sci. Technol.* 48, 9573–9581. doi: 10.1021/es501615x
Stramma, L., Johnson, G. C., Sprintall, J., and Mohrholz, V. (2008). Expanding oxygen-minimum zones in the tropical oceans. *Science* 320, 655–658. doi: 10.1126/science.1153847
Swalwell, J. E., Ribalet, F., and Armbrust, E. V. (2011). SeaFlow: a novel underway flow-cytometer for continuous observations of phytoplankton in the ocean. *Limnol. Oceanogr. Methods* 9, 466–477. doi: 10.4319/lom.2011.9.466
Tanhua, T., Orr, J. C., Lorenzoni, L., and Hansson, L. (2015). Increasing ocean carbon and ocean acidification. *WMO Bull.* 64, 48–51.
Taylor, G. T., Muller-Karger, F. E., Thunell, R. C., Scranton, M. I., Astor, Y., and Troccoli, L. (2012). Ecosystem responses in the southern Caribbean Sea to global climate change. *Proc. Natl. Acad. Sci. U.S.A.* 109, 19315–19320. doi: 10.1073/pnas.1207514109
Thyssen, M., Grégori, G. J., Grisoni, J. M., Pedrotti, M. L., Mousseau, L., Artigas, L. F., et al. (2014). Onset of the spring bloom in the northwestern Mediterranean Sea: influence of environmental pulse events on the in situ hourly-scale dynamics of the phytoplankton community structure. *Front. Microbiol.* 5:387. doi: 10.3389/fmicb.2014.00387
Thyssen, M., Mathieu, D., Garcia, N., and Denis, M. (2008). Short-term variation of phytoplankton assemblages in Mediterranean coastal waters recorded with an automated submerged flow cytometer. *J. Plank. Res.* 30, 1027–1040. doi: 10.1093/plankt/fbn054
Ussler, W. III, Preston, C. M., Tavormina, P., Pargett, D., Jensen, S., and Roman, B. (2013). Autonomous in situ quantitative PCR amplification of aerobic methanotroph genes in the deep sea. *Environ. Sci. Technol.* 47, 9339–9346. doi: 10.1021/es4023199
Valdés, L., and Lomas, M. W. (2017). "New light for ship-based time series," in *What are Marine Ecological Time Series telling us about the ocean?* A status report, Technical Series, No. 129, eds T. D. O'Brien, L. Lorenzoni, K. Isensee, and L. Valdés (Paris: IOC-UNESCO), 297.
Wang, Z. A., Sonnichsen, F. N., Bradley, A. M., Hoering, H. A., Lanagan, T. M., and Chu, S. N. (2015). An in-situ sensor technology for simultaneous spectrophotometric measurements of seawater total dissolved inorganic carbon and pH. *Environ. Sci. Technol.* 49, 4441–4444. doi: 10.1021/es504893n
Yang, B., Emerson, S. R., and Peña, M. A. (2018). The effect of the 2013-2016 high temperature anomaly in the subarctic northeast Pacific (the "Blob") on net community production. *Biogeosciences* 15, 6747–6759. doi: 10.5194/bg-2018-2246
Zibordi, G., Mélin, F., Voss, K. J., Johnson, B. C., Franz, B. A., and Kiwatkowska, E. (2015). System vicarious calibration for ocean color climate change applications: requirements for in situ data. *Rem. Sens. Environ.* 159, 361–369. doi: 10.1016/j.rse.2014.12.015

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frontiers in Marine Science

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A Surface Ocean CO_2 Reference Network, SOCONET and Associated Marine Boundary Layer CO_2 Measurements

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The Surface Ocean CO_2 NETwork (SOCONET) and atmospheric Marine Boundary Layer (MBL) CO_2 measurements from ships and buoys focus on the operational aspects of measurements of CO_2 in both the ocean surface and atmospheric MBLs. The goal is to provide accurate pCO_2 data to within 2 micro atmosphere (μatm) for surface ocean and 0.2 parts per million (ppm) for MBL measurements following rigorous best practices, calibration and intercomparison procedures. Platforms and data will be tracked in near real-time and final quality-controlled data will be provided to the community within a year. The network, involving partners worldwide, will aid in production of important products such as maps of monthly resolved surface ocean CO_2 and air-sea CO_2 flux measurements. These products and other derivatives using surface ocean and MBL

CO_2 data, such as surface ocean pH maps and MBL CO_2 maps, will be of high value for policy assessments and socio-economic decisions regarding the role of the ocean in sequestering anthropogenic CO_2 and how this uptake is impacting ocean health by ocean acidification. SOCONET has an open ocean emphasis but will work with regional (coastal) networks. It will liaise with intergovernmental science organizations such as Global Atmosphere Watch (GAW), and the joint committee for and ocean and marine meteorology (JCOMM). Here we describe the details of this emerging network and its proposed operations and practices.

Keywords: carbon dioxide, network, oceanography, fluxes, best practices

INTRODUCTION

Rising carbon dioxide (CO_2) levels in the atmosphere and ocean are major issues of our time. Historically, the main focus in carbon cycle research has been on understanding the flow and partitioning of the excess carbon dioxide in the earth system components of atmosphere, ocean and terrestrial biosphere. Revelle and Suess (1957) stated "*Human beings are now carrying out a large scale geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future*." Roger Revelle subsequently wrote that "*People's attitude toward the rise of CO_2 should probably contain more curiosity than apprehension*." (Weart, 2008). The basic understanding of processes and impacts remains a priority in carbon cycle research but concerns and societal implications of the impacts of rising CO_2 have surpassed mere curiosity. Increasing emphasis in carbon cycle research is placed on monitoring and quantifying the sources and sinks of atmospheric CO_2, and the interplay between the anthropogenic CO_2, that is, CO_2 released by human activities such as fossil fuel burning and land-use changes, and the natural carbon cycle. This requires a systematic and sustained observational approach, well served by a closely coordinated network. The ocean is a significant sink of anthropogenic CO_2 capturing about 25% of the anthropogenic carbon from 1870–2017 (Le Quéré et al., 2018). Once sequestered by the ocean, the retention time is on the order of centuries to millennia, compared to decades for terrestrial systems. The uptake of CO_2 by the ocean is thus a critical element in understanding carbon dynamics and future trajectories of atmospheric CO_2 growth.

Accurate measurements of CO_2 concentrations in the surface ocean and atmospheric marine boundary layer (MBL) are critical factors to quantify the air-sea flux of CO_2, along with the forcing function, called the gas transfer velocity, k. The air-sea CO_2 flux, F_{CO2} [mol m^{-2} yr^{-1}] is commonly expressed in terms of a bulk formulation as:

$$F_{CO2} = k\,s(pCO_{2w} - pCO_{2a}) = k\,s\Delta pCO_2 \quad (1)$$

where k [m yr^{-1}] is parameterized with wind (Wanninkhof, 2014), s is the solubility [mol m^{-3} atm^{-1}], pCO_{2w} is the partial pressure of CO_2 in water [atm], pCO_{2a} is the partial pressure of CO_2 in air [atm], and ΔpCO_2 is the difference. The units for k, s, and pCO_2 are often reported as cm hr^{-1}, mol l^{-1} atm^{-1}, and μatm, respectively, and appropriate conversions need to be applied. The quantities measured are the mole fractions of CO_2 in water, xCO_{2w}, and air, xCO_{2a}, and these are converted to partial pressure with knowledge of the total pressure and water vapor pressure (Pierrot et al., 2009). While ΔpCO_2 over the open ocean can vary in time and space by about $\pm$ 100 μatm, the average disequilibrium needed to sequester the current annual ocean uptake of 2.5 billion tons of anthropogenic carbon (2.5 Pg C yr^{-1}) (Le Quéré et al., 2018) is only 7–14 μatm, requiring accurate measurements of pCO_{2w} and pCO_{2a} with high spatiotemporal resolution. Due to the small average disequilibrium, measurements must be accurate. Bias, in particular, can be a major issue and thus well-calibrated measurements are a must. Of note is that in Eq. 1 the concentrations right at the interface are of relevance. The measurements, typically at 0.2–8 m depth and 1–20 m height, need to be corrected to surface conditions requiring adjustments for temperature, pressure, and chemical effects. The corrections are largest and most uncertain on the water-side of the interface.

The sequestration of anthropogenic CO_2 emissions by the ocean is of benefit as it curtails increasing atmospheric CO_2 level and its associated greenhouse effect, but the corresponding CO_2 increase in ocean surface waters also leads to ocean acidification (OA), which is detrimental to many marine organisms. Knowledge of the rate of CO_2 uptake and changes thereof are of importance for socio-economic assessments related to the fate of anthropogenic CO_2 and to ocean health.

Systematic measurement of atmospheric CO_2 concentrations began in the late 1950s (Keeling, 1958) to investigate the long-term atmospheric trend of this important greenhouse gas. The discovery of seasonal variability, resulting from terrestrial biosphere CO_2 uptake and release, prompted a small global network of measurements to assess the global distribution of the seasonal and long-term features in CO_2 (Keeling, 2008). As such, initial CO_2 measurements were made from locations where well-mixed MBL air could be sampled, usually coastal or island sites with prevailing onshore winds, so that the data were representative of the regional background CO_2 concentration, and not unduly influenced by localized sources and sinks.

Today, there are more than 100 sites where atmospheric scientists make sustained high-accuracy measurements of atmospheric CO_2. However, the open ocean MBL remains undersampled. Many of these oceanic regions are visited by research vessels and commercial ships of opportunity (SOOP) equipped with underway pCO_{2w} systems that also make routine measurements of CO_2 in the MBL. The atmospheric CO_2 data from these ocean community CO_2 systems do not, however, typically meet the rigorous standards of the atmospheric CO_2 measurement community, as set out in the World Meteorological Organization (WMO) Global Atmosphere Watch (GAW). Much of this data is currently not quality controlled. If the MBL CO_2 data from these ocean community measurement systems can be validated, and where necessary improved, this could lead to mutual benefits for both oceanographers and atmospheric scientists. As described below, based on initial comparisons and analyzer performance on underway systems, an accuracy of 0.2 ppm can be reached with these systems. While this is less accurate than the targets of global atmospheric CO_2 measurements, such calibrated measurements can be used effectively for constraining air-sea CO_2 fluxes, and in inverse models.

Surface ocean CO_2 measurements have been performed onboard ships for over 50 years (Takahashi, 1961; Keeling, 1965) using approaches that are similar to current measurements, but the observations have become increasingly more automated. Unattended measurements referenced against compressed air standards traceable to atmospheric CO_2 standards are now done routinely on ships and, since the 2000s, on moorings (Sutton et al., 2014). The measurements cover much of the global ocean, and allow regular access to regions of economic and environmental importance such as upwelling regions (González-Dávila et al., 2017). Many of the measurements are performed following standard operating procedures (e.g., Pierrot et al., 2009) and much of the data are submitted to global datasets and undergo independent secondary quality control. However, there is no global coordinated effort at the operational level for the data acquisition from ships and moorings as is proposed here for SOCONET.

This paper outlines the ongoing efforts to use established assets to create a reference network for high-quality surface ocean CO_2 observations from SOOP and moorings. As part of the effort we will assess current accuracy and develop protocols for improvement of MBL measurements. The effort is focused on the operational aspect, that is, the operations and tracking of the platforms; acquisition of the data; and their validation. The scientific justifications and resulting products are briefly described. While the need of global coordination has been highlighted over the last decade (Bender et al., 2002; Monteiro et al., 2010; Wanninkhof et al., 2012), the description and justification of doing so in a systems/network approach has been lacking. SOCONET is its developmental stages, and details have not been worked out and implemented. This community white paper was developed from two abstracts for the OceanObs'19 conference, one focused on MBL and the other on the surface ocean CO_2 measurements. The ideas described should be considered in a conceptual framework. The high-level scientific output and socioeconomic motivations are described first, followed by a discussion of the distributed network design, deliverables and challenges to establish the reference network. **Table 1** provides a list of the acronyms and abbreviations used in this work.

SOCIETAL AND SCIENTIFIC IMPERATIVES FOR SOCONET

CO_2 is an important anthropogenic greenhouse gas, and a major driver of climate change that has, and will continue to have, far reaching consequences for our society. Its relevance is highlighted as an Essential Climate Variable (ECV) in the atmosphere and the ocean (as part of the inorganic carbon system), as well as a biogeochemical Essential Ocean Variable (EOV). CO_2 is produced by, for instance, the burning of fossil fuels, aerobic respiration, and oxidation of organic matter. At the most basic valuation this byproduct, or waste product, has an economic cost/value associated with it. Its cost/value has depended on speculation and has been affected by failures in the dedicated commodity markets. It currently is mostly traded as an "emission allowance" as part of a cap and trade system (re)instituted after the Paris Agreement. The largest trading system currently is the European Union (EU) emission trading scheme (ETS). The emission allowances in the EU ETS are equivalent to the right to emit one ton of CO_2 (or 270 kg of C). While ocean carbon uptake is currently not part of the trading scheme, at the valuation listed it would have an annual value of 170 billion US dollars ($) (D'Maris and Andrew, 2017). This is based on a 2.5 Pg C yr^{-1} ocean uptake and a price of $19 per ton CO_2.

While the uptake of CO_2 by the ocean is not included in ETS, its value is recognized as an ecosystem service. The sequestration comes at a cost though in that the resulting elevated CO_2 levels cause ocean acidification which impact ocean biota (see **Appendix A**). This, in turn, can have major effects on fisheries, tourism and other activities contributing to the marine economy. There are no estimates of the current dollar cost of the global impact of ocean acidification but an economic assessment of the impact of a future "OA catastrophe" ranges from a total cost of $97 billion to $301 billion (Colt and Knapp, 2016). While from an economic perspective the possible benefits of CO_2 uptake, expressed per annum above, are greater than the total ecosystem service losses, such an analysis is overly simplistic and does not take the significant societal impacts into account. The socio-economic take-home message is that the anthropogenic component of the carbon cycle translates into many billions of dollars, and impacts ecosystem health and human well-being. It thus requires thorough investigation and monitoring.

Following the adage that anything of significant value needs to be tracked, many aspects of the global carbon cycle require monitoring. In particular, the stocks (inventories) of the major reservoirs and flows (fluxes) at the interfaces between the atmospheric, oceanic, and terrestrial boundaries need to be quantified. Many parts of the systems are monitored following well-developed network principles and data acquisition. The data from these networks are the cornerstone of increasingly sophisticated products benefitting from robust modeling frameworks. Of particular interest in developing SOCONET and MBL CO_2 monitoring has been the development of the European Integrated Carbon Observation System (ICOS) which is a distributed network primarily based on established research entities incorporating oceanic, atmospheric

TABLE 1 | Acronyms and Abbreviations.

ACT	Alliance for Coastal Technologies, www.act-us.info/
CCL	Central Calibration Laboratory
CCGG	Carbon Cycle and Greenhouse Gas network www.esrl.noaa.gov/gmd/ccgg/mbl/index.html
DBCP	Data Buoy Cooperation Panel of JCOMM
ERDDAP	Environmental Research Division Data Access Program, https://coastwatch.pfeg.noaa.gov/erddap/index.html
ESRL	Earth System Research Laboratory of NOAA
EU	European Union
FOO	Framework for Ocean Observing of GOOS, www.oceanobs09.net/foo/
GAW	Global Atmosphere Watch of WMO, http://www.wmo.int/gaw
GCOS	Global Climate Observing System
GCP	Global Carbon Project, www.globalcarbonproject.org
GMD	Global Monitoring Division of NOAA/ESRL
GOA-ON	The Global Ocean Acidification Observing Network
GOOS	Global Ocean Observing System
GOSUD	Global Ocean Surface Underway Data project
ICOS	Integrated Carbon Observation System, a European Research Infrastructure, www.icos-ri.eu
IG3IS	Integrated Global Greenhouse Gas Information System, www.wmo.int/pages/prog/arep/gaw/ghg/IG3IS-info.html
IOC	Intergovernmental Oceanographic Commission of UNESCO www.ioc-unesco.org/
IOCCP	International ocean carbon coordination project, http://ioccp.org
JCOMM	the Joint WMO-IOC Committee for Ocean and Marine Meteorology, www.jcomm.info
JMA	Japan Meteorological Agency
LDEO	Lamont-Doherty Earth Observatory of Columbia University
NOAA	National Oceanic and Atmospheric Administration
OCG	Observation Coordination Group of JCOMM
OCO-2	Orbiting CO_2 Observatory 2, https://co2.jpl.nasa.gov/#mission=OCO-2
OPA	Observations Program Area of JCOMM
SOCAT	Surface Ocean CO_2 Atlas; www.socat.info
SOCOM	Surface Ocean pCO_2 Mapping intercomparison
SOCONET	Surface Ocean CO_2 reference Network, www.soconet.info
TCCON	Total Carbon Column Observing Network, https://tccon-wiki.caltech.edu/
TransCom	Atmospheric Tracer Transport Model Intercomparison Project, transcom.lsce.ipsl.fr/transcom.lsce.ipsl.fr/
WDCGG	World Data Centre for Greenhouse Gases, https://gaw.kishou.go.jp/
WMO	World Meteorological Organization, https://public.wmo.int/en
AI	Artificial Intelligence
ASV	Autonomous Surface Vehicles
BGC	Biogeochemistry
CO_2	Carbon dioxide
DIC	(Total) Dissolved Inorganic Carbon
ECV	Essential Climate Variable, https:public.wmo.int/en/programmes/global-climate-observing-system/essential-limate-variables
EOV	Essential Ocean Variable, http://www.goosocean.org/eov
ETS	Emission Trading Scheme
FAIR	Findable, Accessible, Interoperable and Reusable
H_2O	Water (vapor)
MBL	Marine Boundary Layer
NN	Neural Network
OA	Ocean Acidification
OSE	Observing System Experiment
OSSE	Observing System Simulation Experiment
pCO_{2a}	Partial pressure of carbon dioxide in air
pCO_{2w}	Partial pressure of carbon dioxide in water
Pg C	Petagram of carbon (10^{15} g; 10^9 ton)
ppm	Parts per million (10^{-6})
REBS	Robust Extraction of Baseline Signal
SOM	Self Organizing Map
SOOP	Ship of Opportunity Program
SOP	Standard Operating Procedures
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
TAlk	Total Alkalinity
TSG	(Surface ocean) thermosalinograph
TT	Target Tank
VOS	Volunteer Observing Ship

Organizations and programs including some of the associated websites.

and terrestrial components. This approach of going from measurements in research projects to a sustained monitoring network following clear protocols can guide development of SOCONET.

Surface Ocean CO_2 NETwork will be a major contributor of reference quality observations to quantify air-sea CO_2 fluxes on seasonal to interannual scales, and to determine trends in pCO_{2w} levels over time. To deliver the global products on a regular and anticipated basis, it must be a global effort of sustained nature, and a network approach is most practical (**Table 2**). Networks are best established through a single source of funding/agency, with strong oversight and leadership, and uniform instrumentation. However, this is rarely achievable for global ocean networks focused on climate and environmental issues. The closest example in oceanography is the successful Argo profiling float network. SOCONET will be a distributed network involving many groups. It will provide coordination and homogenization of nationally funded efforts on a global level. The execution of the primary objectives rely on several other components and additional measurements. Besides accurate air and ocean water measurements provided by the SOCONET partners, data from other sources needs to be included through activities such as the Surface Ocean CO_2 Atlas, SOCAT (Bakker et al., 2016) and mapping efforts such as SOCOM (Rödenbeck et al., 2015; **Figure 1**).

Surface Ocean CO_2 NETwork is largely an operational entity but must be justified through delivery of (improved) products of scientific and socio-economic value. The major products that SOCONET will contribute to are surface ocean pCO_2 maps and air-sea CO_2 fluxes on monthly scales and with spatial resolution of 1°. The data need to be interpolated in time and space, and combined with other environmental parameters to create such maps (**Figure 1**). These maps rely on high-density data, often from satellite remote sensing (Shutler et al., 2019) and increasingly more sophisticated regression approaches, including machine learning such as neural networks (NN), and self-organizing maps (SOM) (Rödenbeck et al., 2015). Furthermore, possibilities of utilizing artificial intelligence (AI) approaches are being considered. Aside from application to determine the air-sea concentration difference (Eq. 1), the atmospheric CO_2 measurements will be used by atmospheric inverse modeling teams to generate improved estimates of CO_2 fluxes over oceans and adjacent continents (Jacobson et al., 2007; Gaubert et al., 2019).

These products and inputs are the cornerstones of derivatives, such as estimates of trends in uptake. The F_{CO2} estimates are currently used to test and benchmark carbon sink estimates derived from "bottom-up" ocean process models, many of which are used to predict future scenarios of global and regional climate change. The creation of surface pH maps using pCO_{2w} as a primary variable, as part of the verifying targets of Sustainable Development Goal 14.3 is another important product. The needs for the products are articulated at high levels, such as the Global Carbon Project (GCP) that produces annual data-based estimates of fluxes between the major carbon reservoirs (Le Quéré et al., 2018), and the Global Climate Observing System (GCOS) that has called ocean acidification a headline indicator of changes in biogeochemistry in the ocean due to climate change.

TABLE 2 | Attributes of a JCOMM Network.

Global in scale	Greater than regional, and as far as feasible, intention to be global.
Sustained observations	Sustained over multiple years, beyond time-span of single research or experimental projects.
Community of practice	Has an identified community governance structure that provides a means of developing a multi-year strategy, implementation plans and targets, and standards and best practices.
Delivers data that are free, open, and available in a timely manner	Has a defined data management infrastructure that delivers interoperable and inter-comparable data in real-time and/or with minimal delay after becoming available.
Observes one or more Essential Ocean Variable or Essential Climate Variable	Contributes to meeting requirements through observing one or more of the GOOS EOVs or GCOS ECVs.
Maintains network mission and targets	The role in GOOS is defined and progress toward targets can be tracked and progress assessed.
Develops, updates and follows standards and best practices	Provides standard operating procedures that are readily accessible and citable.

THE ESTABLISHMENT OF SOCONET

Network Principles

The SOCONET network development follows the network attributes proposed by the Observation Coordination Group (OCG) of JCOMM. This will facilitate incorporation of SOCONET within the JCOMM construct (**Table 2**). From an operational network perspective, a multi-PI distributed international network is challenging but benefits from human capital including expertise, innovation and oversight. The development of SOCONET relies heavily on established interactions in SOCAT. SOCAT is a well-designed data collation, quality check and distribution system of surface ocean pCO_2 measurements (Bakker et al., 2016). SOCAT is not directly involved in the operational aspects of data acquisition that is the focus of SOCONET. A schematic of the interaction of SOCONET and SOCAT and the more informal product development efforts, such as the surface ocean pCO_2 mapping intercomparison project, SOCOM is shown in **Figure 2**. Admission to SOCONET is selective based on meeting the network criteria. SOCONET will initially only include platforms that meet the data quality and release schedule as outlined in **Table 3**. The full details of SOCONET, that is focused on the operations of surface ocean CO_2 measurements, can be found in the SOCONET prospectus (Wanninkhof et al., 2018) with a brief summary below.

Surface Ocean CO_2 NETwork will cover key regions of the ocean (**Figure 3**) with data of specified quality. It will perform measurements following documented procedures and network practices including: common protocols, similar instrumentation, and standardization. It will provide standard operating procedures (SOPs) for acquiring the data. Data will be appropriately documented with metadata compliant with international protocols, and accuracy and precision requirements. Surface water pCO_2 data from SOCONET will be submitted through the established SOCAT data system. The platforms will be tracked through the JCOMMOPS platform management system and tagged as SOCONET reference network data. The network will be constructed within the Framework for Ocean Observing (FOO) of the Global Ocean Observing System (GOOS) and in accord with FOO mission statement:

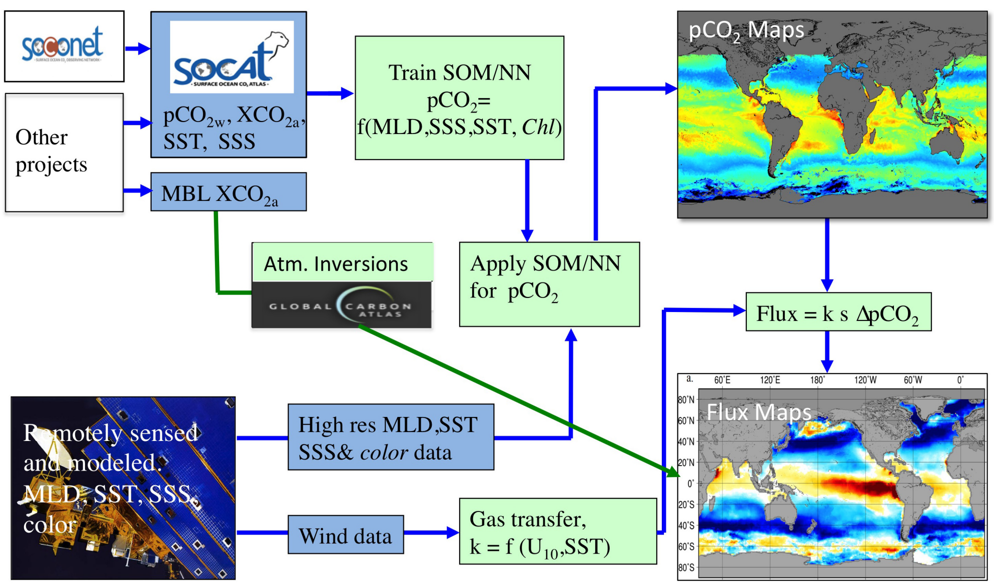


FIGURE 1 | Schematic how SOCONET and MBL CO_2 data will contribute to the creation of surface ocean pCO_2 maps and CO_2 flux maps. The blue boxes indicate data products and the light green boxes indicate the manipulations/calculations to the maps. This conceptual drawing indicates the many steps necessary to go from observations to products.

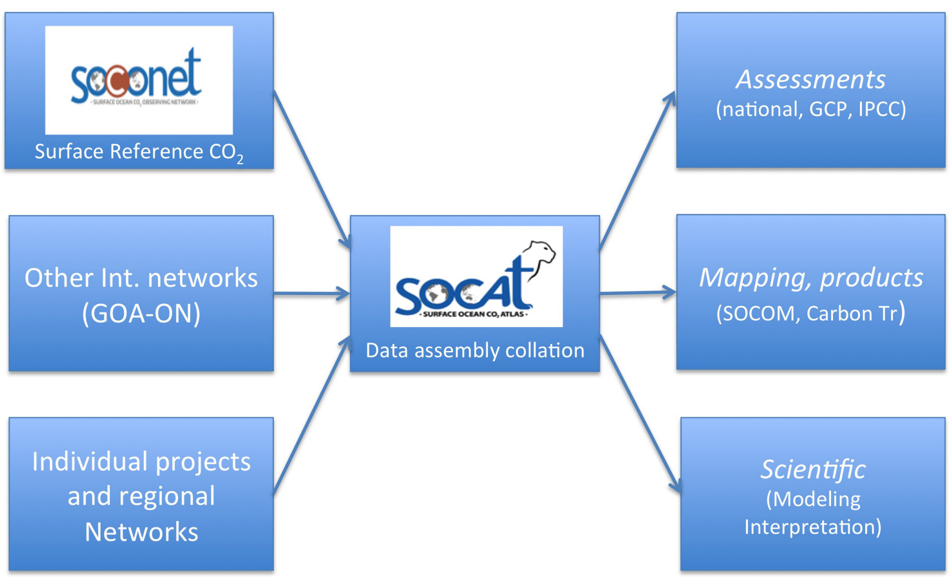


FIGURE 2 | Flow diagram that shows the relationship between SOCONET, SOCAT and other activities.

"A framework for moving global sustained ocean observations forward in the next decade, integrating feasible new biogeochemical, ecosystem, and physical observations while sustaining present observations, and considering how best to take advantage of existing structures."

The objectives and criteria of the SOCONET reference network are provided in **Table 3**.

Platform Types

Surface Ocean CO_2 NETwork is envisioned as a multi-platform EOV-based network, but currently only includes instruments on moorings and ships. The differences and attributes of the platforms are shown in **Table 4**. The strengths and weaknesses of each platform listed are generalities, and vary for each individual platform, but it serves to show issues and challenges that require further attention. There are several other autonomous platforms and instruments that could be part of SOCONET in the future. However, each needs to be fully vetted in meeting the criteria specified in **Table 3**. Of particular use in this respect are instrument intercomparison exercises, and side-by-side comparisons to assure new platforms and instruments meet the requirements. Regular intercomparison activities are envisioned in collaboration with national and regional efforts, and coordination groups such as the alliance for coastal technologies (ACT) and the International Ocean Carbon Coordination Project (IOCCP).

Data Management, Access and Quality Control

The data management framework developed under SOCAT (Pfeil et al., 2013; Bakker et al., 2016) will also serve as the data depository for SOCONET surface water CO_2 data (**Figure 2**), and likely for the MBL CO_2 taken in conjunction with surface ocean pCO_2. Over the last several years, the SOCAT data

TABLE 3 | Synopsis of SOCONET objectives and criteria.

Activity	Criteria
Membership	Partners have a track record of operations and will follow agreed upon procedures to obtain quality measurements.
Observational target	The compatibility (i.e., the allowable difference from a recognized scale) CO_2 measurements are better than 2 μatm for water (pCO_{2w}) and 0.2 ppm for air (xCO_{2a}).
Data delivery	Quality controlled reference data in 6 to 12 months.
Tracking	Near real-time platform tracking with location updates at least once a day.
Oversight	Metrics on data quality and quantity are provided on an annual basis.
Quality assurance	Quality assessment intercomparison exercises are performed to assure that standards are met.
Quality assurance	Instruments checked before installation, during operation, and after recovery of systems.
Deliverables	A dataset of reference network data will be created once a year.
Collaborate	Mutual aid, exchange and assistance are provided by SOCONET members for addressing technical issues in operations.
Outreach	Scientific outreach focuses on elevating quality and providing assistance to other groups in sustaining quality observations with a goal to entrain additional platforms into the network.
Outreach	The SOCONET members provide input and guidance to the community on new platforms, measurements, and protocols with a vision toward implementing a biogeochemical network and supporting marine boundary layer atmospheric measurements.
Connection to WMO/IOC/JCOMM	The network funders will provide resources toward tracking platforms through JCOMMOPS and other agreed upon mutual services.

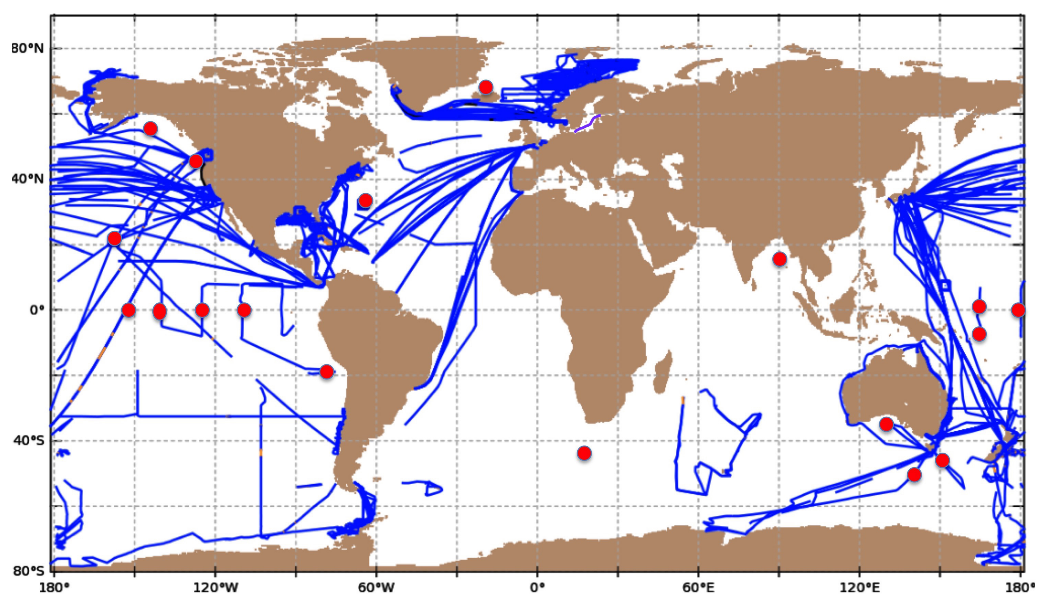
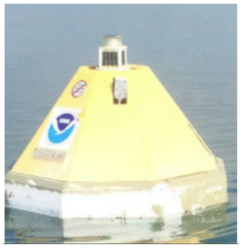


FIGURE 3 | Ship lines and moorings that currently meet SOCONET data quality and are potential contributors to the SOCONET effort. Lines are based on the SOCAT holdings from 2017 to 2018 with pCO_2 data that are believed to be accurate to within 2 μatm. The mooring sites with systems meeting the data quality standards are indicated by red circles.

TABLE 4 | Platforms used in SOCONET[1].

	Moorings provide high-resolution temporal coverage and provide measurements closest to *in situ* conditions, they currently operate with a span gas but no target gas to verify concentrations such that accuracies are estimated from intercomparisons and pre- and post-cruise calibration/verification. Moored air CO_2 measurements have not yet been validated to meet a target of 0.2 ppm.
	Cargo ships provide regular observations with weekly to bimonthly repeat occupations offering seasonal resolution. Observations are along commerce routes, but miss coverage of key areas such as the South Indian and high latitude oceans. Instruments are often placed in inhospitable environments such as engine rooms degrading their performance. Water and air intakes depend on established infrastructure and are not always optimal.
	Cruise ships and ferries provide high quality observations with weekly to biweekly repeats often with better installation options than cargo ships. The ships provide good outreach opportunities and exposure.
	Research ships have infrastructure and support for quality measurements. Instrument locations are good. The ships often travel beyond shipping lanes and to regions of physical and biogeochemical interest (such as "hotspots). Other projects provide added value. Cruise tracks are not frequently occupied and other activities can compromise (air) measurements.
	Ice breakers and polar supply ships travel to regions of high interest, often at regular intervals. Infrastructure of ships facilitate operations of underway pCO_2 systems. Other science projects often take place and provide value added both for interpretation of pCO_2 and for the projects.

[1] *These are examples of platforms with instruments that meet SOCONET criteria based on intercomparisons and guidelines (see* ***Table 3****). The comments are generalities. For example, some installations on cargo ships are superior to research ships.*

team has improved the submission, quality control, access and archival processes that support the annual releases of the SOCAT data products. These data products are available to the public through the web site, www.socat.info and are archived with persistent identifiers (doi's) provided. In addition, the SOCAT data products are made available through the ERDDAP data platform, providing interoperable access to the datasets through a wide variety of tools and machine-to-machine services. Discovery and visualization services are provided for the SOCAT data through NOAA's Live Access Server. By leveraging this framework, SOCAT, and therefore SOCONET, supports the FAIR (Findable, Accessible, Interoperable and Reusable) data principles for improved levels of data interoperability and reuse. The automated system used by SOCAT demonstrates a method to efficiently manage the larger volumes of data expected with the future of new ocean observing efforts and can support the emerging SOCONET.

CONTRIBUTIONS OF SOCONET

Improved Understanding, Basic Research

Surface Ocean CO_2 NETwork is, in part, a research network that delivers data for basic discovery and understanding of processes and mechanisms. Thus, the network will be used for more than the operational production of maps. This is important as there is a lack of understanding of the effect of variations and change in climate and ocean condition on CO_2 levels, including the possibility of thresholds, tipping points, and feedbacks. The high quality needs and challenges of making the exacting measurements require extensive basic understanding, instrumental expertise and manual quality control requires a firm knowledge of the processes and instrumental analysis.

Research questions relating to climate and ecosystem changes benefit from sustained observations. There are a series of research questions that can, in part, be addressed with data from SOCONET platforms including quantifying the physical parameters impacting air-sea CO_2 exchange (e.g., Zappa et al., 2004); the impact of the biological pump on surface ocean CO_2 levels (e.g., Merlivat et al., 2015); feedbacks of calcifying organisms on surface water CO_2 (e.g., Frankignoulle et al., 1994); the control and changes of biogeochemical process (e.g., Schneider and Müller, 2018); and the response of surface ocean CO_2 levels to changes in atmospheric forcing (e.g., Arora et al., 2013). The latter is of great importance in the socio-economic arena to assess the efficacy of fossil fuel CO_2 reductions in meeting climate accords (Peters et al., 2017) that will require observational validation.

The data from SOCONET platforms will be used to improve the quantification of air-sea CO_2 fluxes through timely updates to algorithms such as those established in SOCOM (Rödenbeck et al., 2015). The observations can also be used in data withholding exercises that provide an independent estimate of the accuracy of the results. The rapid release of data can inform and serve as an early warning to changing patterns and trends, in particular those that are not fully captured in the regression approaches. The data will be critical to validate the results of new sensors and new platforms. Of note is the validation of pCO_2 derived from pH sensors from profiling floats to estimate CO_2 values (Williams et al., 2017). While the derived pCO_2 data from pH provide good precision, the accuracy of the derived pCO_2 is not well constrained and this can be uniquely addressed by validation with accurate *in situ* pCO_2 data.

Network Design

To date there has not been a formal design of a global surface ocean CO_2 network. Bender et al. (2002) provide a broad view of network needs based on de-correlation analyses which were fine-tuned by Li et al. (2005). Regional observing requirements for the Southern Ocean are described in Majkut et al. (2014), and an observing system design for biogeochemistry for this region is described in Kamenkovich et al. (2017). A global surface ocean CO_2 network design has been lacking, in part because there have been no formal collaborations between operators of systems. Moreover, because of the paucity of data, and their many applications, any new data is considered a significant contribution.

Instrument deployment for accurate CO_2 measurements is currently limited to platforms such as ships and moorings, but autonomous surface vehicles (ASV) have the potential to expand the means to obtain data. Data, particularly from the ASVs and research ships that often visit remote ocean regions, will be useful in observing system design. Several approaches such as observing system simulation experiments (OSSE), and observing system experiments (OSE) are available that utilize *a priori* knowledge of the global fields to optimize sampling strategy. These network design approaches, as well as approaches using mapping and data denial experiments will be necessary to justify and implement a comprehensive SOCONET network.

Using pCO_{2w} to Estimate Other Inorganic Carbon Parameters and Develop Products

In addition to using pH to estimate pCO_{2w} (Williams et al., 2017), the reverse needs to be investigated as well (**Appendix A**). The utilization of surface ocean pCO_2 to aid in creating surface ocean pH maps will be an important use of SOCONET data (Lauvset et al., 2015). This is of particular relevance to determine longer-term trends in surface OA that need high accuracy data as called out in UN Sustainable Development Goal (SDG) 14.3 Ocean acidification and climate change. Much of the dedicated OA data are of lower quality focused on larger excursions of pH on sub-seasonal and local scales. These measurements are generally not suited for determining longer-term trends in OA. The Global Ocean Acidification Observing Network, GOA-ON will rely, in part, on SOCONET observations to estimate global patterns and trends. **Figure 4** is an example of a high-resolution monthly pCO_2 map based on a SOM/NN approach. The pCO_{2w} data, along with measurements or estimates of TAlk or DIC, can be used to calculate pH from which surface ocean pH maps can be created applying similar mapping approaches (Takahashi et al., 2014). A major deliverable of SOCONET will be data for improved near-term estimates of air-sea CO_2 fluxes. As described above, there are several other data streams required to determine air-sea CO_2 fluxes, such as remotely sensed winds for estimating the gas transfer velocity, and different parameters to aid interpolation, most notably sea surface temperature (SST) (**Figure 1**).

CONTRIBUTION OF MBL CO_2 OBSERVATIONS

Surface Ocean CO_2 NETwork has a strong focus on accurate pCO_{2w} measurements (**Table 3**), but offers a unique opportunity to contribute to (air) MBL CO_2 data, which are undersampled over the open ocean. Most of the underway pCO_2 systems used in SOCONET take 5 air measurements, 1-min apart, from an intake at the bow or bridge of the ship, at intervals of about 3 h.

Moored pCO_2 systems in SOCONET take an air measurement every 4 h from 0.5 to 1 m on the buoy tower. By developing proper measurement protocols and quality control procedures, these data will be useful for improved MBL and air-sea CO_2 flux products. Here we focus on these measurements and means to verify their accuracy. In addition, there are dedicated instruments on some ships that meet GAW accuracy requirements. These efforts should be expanded, and having both types of instruments on select ships will provide critical information on the quality of the air data from the systems measuring surface water pCO_2. Since the accuracy of MBL CO_2 data from underway CO_2 systems has not been fully investigated, and dedicated MBL systems meeting GAW accuracy requirements are costly, the air MBL requirements for SOCONET are under discussion and development. Below we describe the justification and current status.

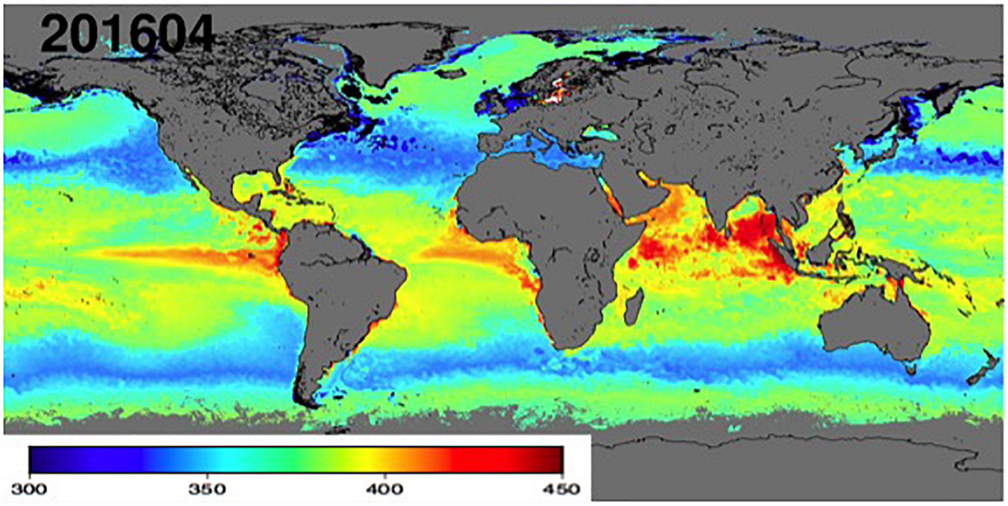


FIGURE 4 | Monthly map of pCO_{2w} for April 2016 created by a NN/SOM method showing the high fidelity of the output taking advantage of high-resolution remote sensing data. This example uses SOCAT data as the training set (units: μatm) (J. Triñanes, pers. com.).

Justification for Making Calibrated Accurate MBL CO_2 Observations From Ships

Here, calibrated accurate CO_2 measurements are those that are compatible to within ± 0.2 ppm of the global CO_2 scale maintained by the WMO/GAW Central Calibration Laboratory (CCL). We propose that this is the quality standard to which ocean community MBL CO_2 measurements should strive. The term accuracy is used instead of precision/repeatability in recognition that imprecise measurement systems can still be sufficiently accurate if the noise in the data is randomly distributed around the "true" value and therefore does not bias the mean values. The MBL CO_2 variability over the ocean interior is smaller than atmospheric CO_2 variability over land, and MBL CO_2 from the relatively imprecise measurements from systems focused on pCO_{2w} should be able to achieve the needed levels through averaging if these systems are appropriately optimized for atmospheric CO_2 measurement and kept well-maintained, but this has not been fully tested. It should be noted that the WMO/GAW ± 0.1 ppm compatibility goal (±0.05 over the Southern Hemisphere) will likely not be attained by the systems measuring pCO_{2w}. Moored air CO_2 measurements have not been validated to yet meet the ± 0.2 ppm goal and this should be an area of focus for improving accuracy of existing moorings. Data of such accuracy from sparsely sampled oceanic regions will be beneficial to atmospheric inverse modelers as long as their accuracy is quantified and described in the metadata. Moreover, this level of accuracy will not introduce a significant error in the air-sea fluxes where the uncertainty in the concentration gradient is dominated by the pCO_{2w} measurements that are good to within ± 2 μatm.

Validating and improving the quality of oceanic MBL CO_2 measurements is mutually beneficial to both the ocean and atmospheric research communities. One of the key advantages for the ocean community is the improvement of air-sea CO_2 fluxes (F_{CO2}). While most ships make *in situ* MBL CO_2 measurements, F_{CO2} is not usually calculated using these data. Instead, values for pCO_{2a} (from Eq. 1) are most commonly derived from the MBL reference data product provided by the Global Monitoring Division (GMD) of NOAA/ESRL. This data product is generated from a subset of NOAA atmospheric CO_2 measurement sites near the coast that predominantly experience MBL air. These data are filtered, interpolated, and smoothed prior to being fit at latitudinal intervals of 0.05 sine of latitude from 90°S to 90°N and joined to create a 2-dimensional matrix (time versus latitude) of weekly CO_2 values (Conway et al., 1994; EW Team, 2005). Thus, while this data product is useful for identifying large-scale trends, it does not reflect the full spatial or temporal variability of MBL CO_2 that exists in the atmosphere, as explained in the online documentation and demonstrated previously (Pickers et al., 2017). The implications for F_{CO2} calculated using this product are that in some regions, particularly coastal margins where the effects of continental airflow on MBL CO_2 are not included in the NOAA MBL data product, biases will arise in the air-sea CO_2 fluxes.

Comparing F_{CO2} calculated using different sources of MBL CO_2 data is useful for demonstrating the potential impacts of using inaccurate atmospheric data to calculate fluxes. **Figure 5** shows that air-sea CO_2 fluxes calculated using the observed MBL CO_2 values at the Martha's Vineyard site in Massachusetts, United States (41.3°N, 70.6°W) can differ by up to 15% compared to those calculated using the NOAA MBL product. Mean annual differences between atmospheric CO_2 from the CarbonTracker 2017 modeling system (Peters et al., 2007) and the NOAA MBL reference product can be as high as 20 ppm within coastal seas near industrial centers, which translates into flux differences for these regions that can exceed 0.5 mol m^{-2} yr^{-1} (**Figure 5**). Moored pCO_2 systems, which measure air CO_2, also show

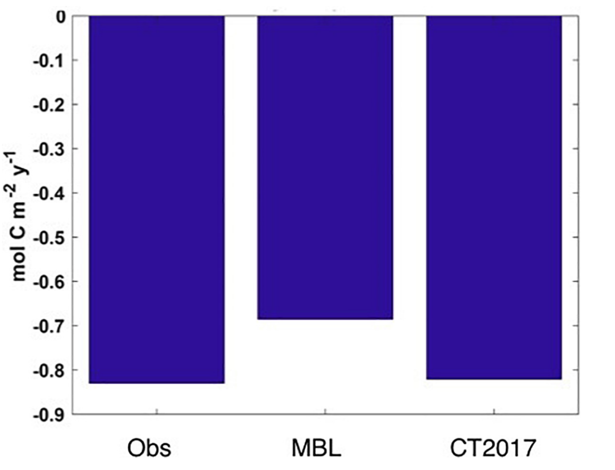


FIGURE 5 | Air-sea CO_2 fluxes at Martha's Vineyard, calculated using three different sources of atmospheric CO_2: *in situ* observations at the site (obs); the NOAA MBL reference product (MBL) and CarbonTracker 2017 (CT2017).

that these measurements can differ from the MBL reference data product in annual mean and seasonal variability due to local and regional effects (Northcott et al., 2019; Sutton et al., 2019). Although the uncertainty associated with pCO_{2a} is often not considered to be significant compared to other sources of uncertainty in Eq. 1, **Figures 5**, **6** indicate that inaccurate atmospheric CO_2 values can lead to significant biases in F_{CO2} at both local and regional scales. Using the *in situ* atmospheric CO_2 data from ships and moorings will likely eliminate these F_{CO2} biases, provided that the MBL CO_2 data are sufficiently accurate and devoid of ship contamination.

Other benefits to the oceanic community from improving or validating shipboard and mooring MBL CO_2 data include increased confidence in CO_2 flux data products that include data from multiple different ships/measurement platforms, and better traceability of pCO_2 data to the Central Calibration Laboratory (CCL) of WMO/GAW currently housed at NOAA/ESRL. The process of upgrading current shipboard CO_2 measurement systems and protocols to facilitate high-accuracy atmospheric CO_2 data from oceanic regions has an associated financial cost. This will require a significant oceanic community effort that should be supported by the collaboration of the atmospheric measurement community.

High-accuracy MBL CO_2 data from ships will benefit the atmospheric research community by substantially augmenting the atmospheric CO_2 measurement network in regions that are currently undersampled. Such data will be of value to the atmospheric inverse modeling community, who estimate surface CO_2 fluxes using a "top-down" approach, an alternative methodology for the calculation of global air-sea CO_2 fluxes to the bulk flux approach (Eq. 1) that utilizes surface ocean pCO_2 measurements (e.g., Takahashi et al., 2009; Landschützer et al., 2013, 2014). The "top-down" approach combines measurements of atmospheric CO_2 (e.g., provided by the surface sampling network of NOAA-GMD) and other global contributors together with information on atmospheric transport (usually from atmospheric transport models), process-based prior flux estimates, and an inverse Bayesian optimization methodology (e.g., Rodgers, 2000). The current generation of such top-down inverse analyses often employ data assimilation or variational methods (e.g., Peters et al., 2007; Chevallier et al., 2010; Kang et al., 2011) and can provide grid-resolved flux-estimates at spatial-scales of ∼10 km to 100 km (e.g., Broquet et al., 2013; Babenhauserheide et al., 2015). While top-down methods provide valuable alternative constraints on surface CO_2 fluxes, they are subject to significant uncertainties in regions of sparse sampling, most notably, in open ocean regions with few fixed sites (Rödenbeck et al., 2006), as well as significant uncertainties relating to atmospheric transport and the data assimilation methodology.

Given the additional cost involved in improved MBL CO_2 data from ships and moorings, interaction with the inverse modeling and observing system design communities will be used to identify regions where the added data have highest impact on uncertainty reduction. Within the European ICOS Network, pilot studies for the acquisition of MBL CO_2 data matching the standards of the atmospheric community are currently underway. SOCONET can make use of these investigations for the design of a network of high-accuracy MBL CO_2 measurement platforms with the aim to maximize the scientific return of investment.

High-Accuracy Atmospheric CO_2 Measurement Approaches and Data Validation

The task of improving oceanic community MBL CO_2 measurements will be approached in two ways: by upgrading existing measurement systems that are not currently optimized for atmospheric CO_2 measurements; and, investment in new, purpose designed measurement systems that employ more modern technologies such as laser-based techniques. It is likely that some ocean community MBL CO_2 data are already sufficiently accurate to be used in F_{CO2} calculations and in inverse modeling studies where highest-accuracy is not required.

However, without validation this cannot be determined at present. Two approaches for improving MBL CO_2 are discussed, as well as the importance of data validation and quality control. Detailed technical information regarding atmospheric CO_2 measurement can be found in WMO/GAW Report 229 (2016) and in the ICOS atmospheric stations specifications document (Laurent, 2017).

Most existing underway pCO_2 measurements are currently made using instrumentation following ocean surface water pCO_2 community design (Pierrot et al., 2009). The systems have been built in-house at different laboratories and are currently available from General Oceanics Ltd. They have both seawater and atmospheric CO_2 measurements capabilities using a non-dispersive infrared (NDIR) analyzer (typically those manufactured by LI-COR Inc.), the traditional method for continuous atmospheric CO_2 measurement. Ocean community MBL CO_2 measurements are typically only required to be accurate to about ± 1 ppm in order to calculate air-sea CO_2 fluxes to specifications (Bender et al., 2002); hence, these measurement systems are not designed for atmospheric CO_2 measurement, with the priority instead focused upon ensuring the highest possible quality of near-continuous pCO_{2w} measurements. As such, the setups of these measurement systems are not optimized for obtaining high-accuracy MBL CO_2. For example, the wetted parts (i.e., the surfaces of components, such as pumps, valves and tubing, that are in contact with the sample air stream) might not be suitable for precise atmospheric CO_2 measurement, sample air drying might not be sufficient (insufficient drying can lead to CO_2 dilution, pressure broadening effects, and surface effects with tubing walls, all of which can bias CO_2 measurement), and there may be small undetected leaks, which can cause non-negligible CO_2 biases owing to the rigorous precision requirements of atmospheric CO_2 measurement. Furthermore, calibration protocols are currently not sufficiently rigorous to meet the compatibility standards aspired to by the atmospheric CO_2 measurement community as outlined in WMO/GAW report

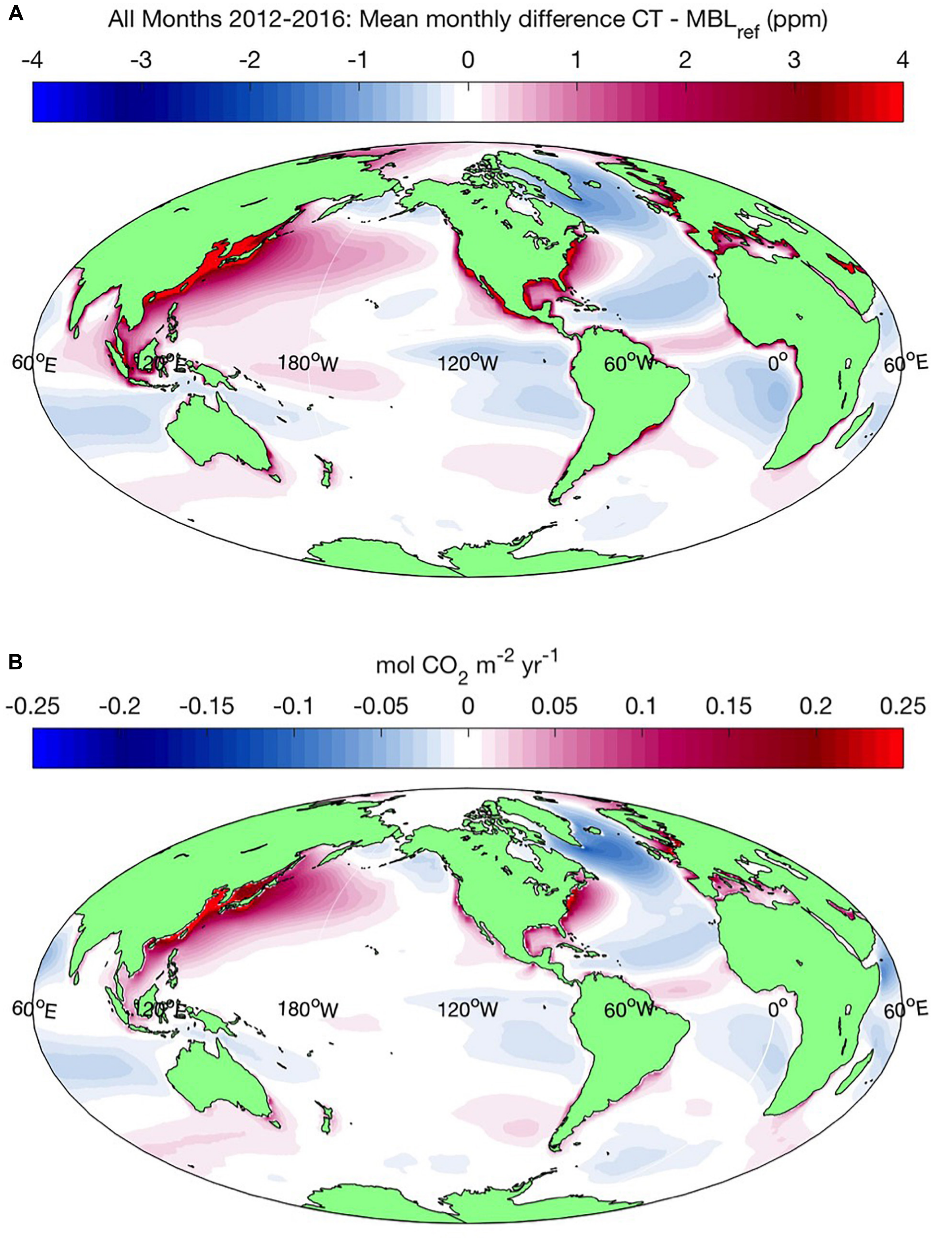


FIGURE 6 | (A) Mean monthly difference in atmospheric CO_2 over the oceans between CT2017 and the NOAA MBL CO_2 reference product, for the period 2012–2016. Note the differences downwind of the northern hemisphere continental land masses; **(B)** annual mean difference in F_{CO2} that arises from using atmospheric CO_2 from CT2017 compared to the NOAA MBL reference product.

no. 229. Nevertheless, with careful adherence to established protocols and procedures, it appears possible to obtain well-calibrated, accurate atmospheric CO_2 data using these existing systems.

Moored pCO_2 measurements in SOCONET are made using an equilibrator- and NDIR-based methodology similar to the underway systems described above. The detector is spanned using WMO-traceable CO_2 reference gas and zeroed using air stripped of CO_2, prior to every measurement. The sample air is not as completely dried as in the underway pCO_2 method (Sutton et al., 2014). Current development efforts are focused on improving accuracy through incorporation of a higher-quality NDIR or other CO_2 analyzer, further drying of air sample, and incorporation of a CO_2 reference/target gas.

The advent of commercial CO_2 analyzers that employ laser-based spectroscopic technology, such as off-axis integrated cavity output spectroscopy (Baer et al., 2002), Fourier transform infrared spectroscopy (Esler et al., 2000), and cavity ring-down spectroscopy (Crosson, 2008) have opened up new opportunities for high-accuracy CO_2 measurement on ships. These spectroscopic analyzers are typically stable for longer periods of time compared to NDIR-based analyzers, thus significantly reducing reference gas (required for differential analyzers) and calibration gas demands. Spectroscopic analyzers usually also have the provision to make sufficiently accurate water vapor corrections compared to NDIR-based analyzers that are not very accurate for H_2O, which can allow for the relaxation of sample air drying requirements. It is important to note, however, that partial drying is normally still required with spectroscopic analyzers, as maintaining a high-accuracy water correction in the field over the full range of ambient atmospheric H_2O concentrations is challenging.

The use of ships for MBL measurements using the new technology is gaining traction with the WMO recognizing the first mobile research station in the GAW in May 2018 on the Australian ship, RV *Investigator*. This ship is equipped with a purpose-built atmospheric monitoring laboratory that reports 1-min measurements of atmospheric CO_2 using a cavity ring down spectrometer. The ship is also equipped with an array of meteorological, radon and carbon particulate sensors that are useful for identifying land-based or ship-stack sources of CO_2. These newer spectroscopic analyzers are much more expensive than NDIR analyzers; they can, however, be used for pCO_{2w} measurement as well as MBL CO_2 measurement, preventing the need to double up on equipment, as demonstrated by Becker et al. (2012). Depending on the model, they are also capable of other underway measurements of interest to the carbon cycle community, such as the stable carbon isotope ratio of CO_2 ($^{13}C/^{12}C$) in water and air (Cheng et al., 2019).

To make an informed decision about how best to obtain high-accuracy MBL CO_2 data (i.e., using existing equipment or investing in new instrumentation), one needs to take into consideration both the scientific goals and logistical constraints (such as space, power requirements, and frequency of maintenance). It is also necessary to address the following question: just how good are the existing data? Verifying the quality of MBL CO_2 data is an important and on-going part of making such measurements, and there are several approaches that can be employed. A highly recommended way is the use of a Target Tank (TT). A TT is a cylinder of dry, natural air that has been measured for CO_2 against the CCL maintained scale before and after it is deployed in the field. The TT is not used to calibrate the system, but is run periodically as a quality control check (e.g., Kozlova and Manning, 2009), to check if the TT CO_2 value obtained from the shipboard measurement system matches the CCL declared value, thus enabling the compatibility of the pCO_2 system to be quantified relative to the laboratory where the TT CO_2 value was declared. The main limitation of TTs is that they usually do not pass through the whole gas handling system (it is generally not practical to feed TT gas through the inlet lines, for example), and so only provide a partial test of the system. The TT can also be used to assess drift of the onboard calibration cylinders.

Other methods that provide a more independent check consist of comparisons with co-located measurements, either from flask samples, which are collected *in situ* and sent to a laboratory for subsequent analysis, or by making use of a "traveling instrument": a completely independent, high-precision continuous measurement system that is installed alongside the existing measurement system for a limited time. The latter approach is used as part of the WMO/GAW station audits in the atmospheric measurement community (Zellweger et al., 2016). Using the flask approach is logistically much easier and can be continued periodically, but does not necessarily help to identify the source of discrepancy in cases where measurements do not agree. Conversely, a traveling instrument can be impractical to implement for a shipboard system and is usually a one-time operation lasting only a few weeks, but is more likely to be able to assist in diagnosing CO_2 offsets.

Employing at least one of the methods mentioned above to regularly validate MBL CO_2 measurements is fundamental to maintaining good data quality, regardless of whether an investigator uses existing equipment or new instrumentation.

A separate issue is that ships are moving platforms that generate their own CO_2 emissions; thus, shipboard CO_2 measurement differs from land-based CO_2 measurement, where stations are typically located remotely from local sources of pollution to avoid data contamination. While efforts are made to locate measurement system inlets as far away as possible from ship exhaust stacks, it is usually unavoidable that some CO_2 emissions from the ship itself will be observed and will need to be filtered out of the dataset, or "flagged," during post-processing. Even if exhaust CO_2 emissions are not often detected (as on some of the larger container ships), any data that is deemed to be "non-background," such as when ships are close to the coast, will also need to be identified. Moorings and wind- or wave-powered ASVs avoid this CO_2 contamination, except when in proximity to a ship or to the coast.

A simple and effective method for flagging non-background values in a MBL CO_2 dataset is to assess the $\pm$ 1σ standard deviation (sd) of the CO_2 values over a specific time period, often an hour (but sometimes a shorter or longer time period is used, depending on the measurement frequency). Other, more sophisticated statistical flagging methods also exist, such as the "REBS" method from El Yazidi et al. (2018), but are not necessarily any better than the sd approach. For ships, it is also often prudent to combine a statistical flagging method with meteorological flagging, whereby data that are measured when the relative wind direction originates from the exhaust stack of the ship and when the absolute wind speed is low are flagged as polluted (e.g., Chapter 3 of Pickers, 2016).

Regardless of the automated flagging method used, some manual quality control/validation of shipboard MBL CO_2 measurements is desirable if these data are to be made available to the wider scientific community via online databases such as SOCAT. Details on quality control activities and who would be responsible are currently being worked out.

PERSPECTIVE AND STATUS OF PRODUCT DEVELOPMENT

The need for ocean carbon networks was articulated in a previous Ocean Observing Conference, OceanObs09 paper (Monteiro et al., 2010) and in an Integrated Ocean Observing System (IOOS) Summit manuscript (Wanninkhof et al., 2012). SOCONET is a refinement of the concepts discussed in these proceedings with more focus on network design, required instrumental accuracy and deliverables. SOCONET aims to contribute data of known high-quality and at regular intervals for three main products: surface ocean CO_2 maps; the global air-sea CO_2 fluxes at monthly resolution and 1° by 1° grid that will be served annually; and MBL CO_2 data to constrain inverse models. These products are in development in research mode by different groups. The inverse models and assimilation approaches such as CarbonTracker are quasi-operational but results can be improved with quality MBL CO_2 data.

Surface maps of ocean acidification can by created in a similar fashion as surface ocean CO_2 maps, utilizing surface ocean pCO_2 data, and estimates or measurements of DIC or TAlk.

These include pH maps but also carbonate ion concentrations and aragonite/calcite saturation state maps. A synopsis of the interrelationships between pCO_2 and inorganic carbon parameters as they pertain to OA are provided in **Appendix A**. The global climatological maps of pH by Jiang et al. (2015) were produced from measurements and interpolation of the relevant ocean acidification parameters calculated from total alkalinity (TAlk) and total dissolved inorganic carbon (DIC). SOCONET will provide data for products that more closely follow the approach of Takahashi et al. (2014) and Lauvset et al. (2015). It uses surface ocean pCO_2 data together with estimates of TAlk based on salinity to determine climatological OA products. The Takahashi et al. (2014) effort includes interpolation and is on monthly resolution and 4° by 5° spacing, and is based on a climatology referenced to year 2010 excluding the Pacific. By creating pCO_2 fields using remotely sensed sea surface temperature (SST) and sea surface salinity (SSS) fields and other high-resolution data, the OA products derived from SOCONET can be created at higher temporal and spatial resolution (Salisbury et al., 2015; Shutler et al., 2019). The approach of assessing OA from pCO_2 measurements may be hindered in coastal settings, such as the Baltic Sea where TAlk and TAlk-SSS relationships may change on similar timescales as pCO_2 (Müller et al., 2016).

There are several efforts to create air-sea CO_2 flux maps. Monthly climatologies at 4° by 5° grids referenced to a particular year are provided in Takahashi et al. (2009). The temporal and spatial gap filling, which is a major consideration in the production of maps, was aided by using a surface velocity field from an ocean circulation model. Lee et al. (1998) and Park et al. (2010) used these pCO_{2w} climatologies to determine changes in time and space by establishing correlations between pCO_2 and SST for each $4° \times 5°$ pixel. This provided the first observation-based estimate of interannual changes in air-sea CO_2 fluxes. More sophisticated approaches have been developed in the last decade, most notably NN and SOM approaches, and data constrained inverse methods. Eleven of the pCO_2 products have been evaluated in a project called SOCOM (Rödenbeck et al., 2015). The detail and complexity of interpolation schemes differ significantly between the various approaches but they all aim to create pCO_2 fields at high resolution from relatively sparse data (**Figure 4**).

Advances in collation of data from groups worldwide have aided the product development. First initiated by Taro Takahashi of LDEO, Columbia University, largely as a single investigator effort, it was communalized under the auspices of IOCCP as the Surface Ocean CO_2 Atlas (SOCAT) effort that provides annual releases of data voluntarily submitted and quality controlled by groups around the globe (Bakker et al., 2016). The value added to the collated dataset is that the data undergo secondary quality control, and pertinent external parameters are added. Standardized metadata and common methods of data acquisition are encouraged, in part, through a ranking of datasets from A through F. Since data sets rated as A and B meet the accuracy standards for SOCONET pCO_{2w} data (**Table 3**), the SOCAT data can be used as an initial screening of platforms. Data products averaged at 1° by 1° for the open ocean and ¼° by ¼° for the coastal ocean are provided by SOCAT as well.

A challenge in producing accurate global surface ocean CO_2 and flux maps is that the magnitudes of longer-term trends in pCO_{2w} are small compared to spatial and temporal variability but their assessments are critical in evaluating the trends of the flux on decadal time-scales (Schuster and Watson, 2007; Landschützer et al., 2014; Iida et al., 2015). Ocean acidification and long term changes in air-sea CO_2 fluxes are driven by increases in atmospheric CO_2 and the resulting disequilibrium between marine air and surface ocean, which is small. This small disequilibrium is difficult to discern. Atmospheric CO_2 values that are currently increasing by 2.4 ppm yr^{-1} and seasonal changes in pCO_{2w} that can be greater than 150 μatm. Regional annual mean differences are over 50 μatm (**Figure 7**). Moreover, near-surface gradients in CO_2 caused by temperature and other physical and chemical effects can influence the CO_2 gradient and flux across the interface. This requires more investigation and could influence operational aspects of SOCONET in the future. An underappreciated fact in view of the large variability is that small systematic biases in pCO_2 measurements and biases

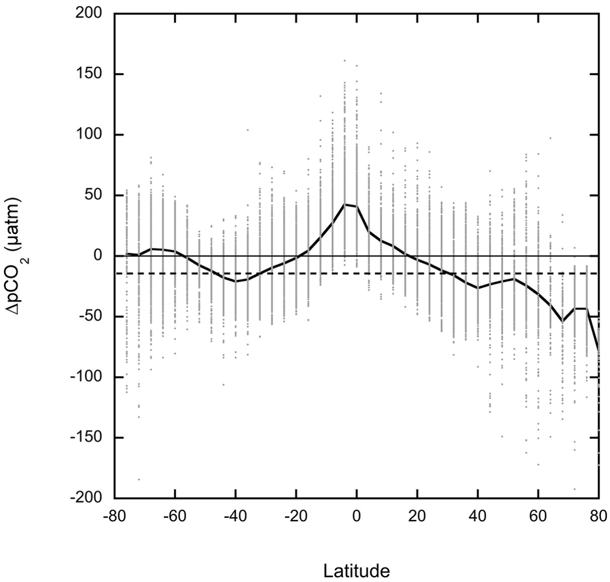


FIGURE 7 | Meridional cross section of the ΔpCO_2 (=pCO_{2w} – pCO_{2a}) climatology of Takahashi et al. (2014). The black line is the annual mean ΔpCO_2 per 4° interval and the gray squares are the monthly averages for the 4° by 5° circumglobal grid boxes for the particular interval. Points above the solid horizontal line (ΔpCO_2 = 0) mean that the area is a CO_2 source to the atmosphere. The dashed line is the average disequilibrium needed for the global ocean to sequester 2.5 Pg C yr^{-1}.

caused by the interpolations over time will have a large impact on quantification of uptake.

It is envisioned that the production of near real-time surface ocean CO_2 maps and CO_2 flux maps will rely heavily on the SOCONET effort. Currently the maps are not created in an operational fashion but tools to do so are under development. The closest to an operational product are the SOM/NN approaches. Summaries of the methodologies to determine surface CO_2 fields and CO_2 fluxes are provided in Rödenbeck et al. (2015) and Zeng et al. (2017). In these efforts the fidelity of the different approaches are critically and objectively investigated, and visualized through, for example, Taylor diagrams such that a concise statistical summary is obtained of how well patterns match each other in terms of their correlation, their root-mean-square difference, and the ratio of their variances (Taylor, 2001; National Center for Atmospheric Research Staff [NCAR], 2013).

All current surface ocean CO_2 mapping efforts rely on interpolation and/or creating algorithms of pCO_2 with environmental fields that are available with high space/time coverage. The ability to create realistic, near real-time maps will depend on the amount of pCO_2 data available, its timeliness, and, because the fluxes are greatly influenced by bias, on the accuracy of pCO_{2w} and pCO_{2a} values. The MBL and surface ocean CO_2 values are systematically changing with time due to emission of anthropogenic CO_2 into the atmosphere, such that obtaining values in a timely fashion is critical.

The need for up-to-date CO_2 values for accurate and timely products is emphasized as current approaches rely on creating relationships of pCO_2 with variables that can be obtained in near real-time through remote sensing, models or from autonomous platforms. The NN and SOM methods that are increasingly used are based on machine learning of patterns and correlations. The relationships are created with different input parameters but generally include SST, location, mixed layer depth, and sometimes SSS, and ocean color. In some approaches there is partitioning based on biogeographic provinces that are effective for the changing ocean (Oliver and Irwin, 2008; Fay and McKinley, 2014). The independent variables change with time, and can change in a different fashion than surface ocean CO_2, such that continued updates using recent pCO_{2w} data are important in order to produce accurate products. Once the correlations in machine learning approaches are established, the approach can be used in absence of actual pCO_{2w} data. However, the products can become biased over time if the algorithms are not updated.

Maps can be created as soon as the independent variables are available; this is in near real-time and within a year with quality control. It is *a priori* assumed that over annual time period the relationship between pCO_{2w} and independent variables is invariant. If pCO_2 data are available in a prompt fashion, these can be used for validation and for updating the parameterizations. A proper collation and quality control mechanisms of recent SOCONET data, and an approach to easily ingest the SOCONET data into algorithms will be essential. Being able to provide up-to-date information of anticipated data through real-time data tracking will facilitate the routine development of products.

CONNECTIVITY TO OTHER SCIENTIFIC EFFORTS AND NETWORKS

Surface Ocean CO_2 NETwork will contribute to other surface ocean networks and the MBL measurements can contribute to atmospheric efforts. This includes the full surface ocean pCO_2 network, whose data are largely captured by SOCAT, and contains pCO_2 data obtained by different types of instruments. Networks that focus on other carbon variables, often associated with OA and ocean health under the GOA-ON purview, will benefit from the SOCONET effort. In addition, the SOCONET effort is closely aligned with GO-SHIP, executed on research ships. Accurate surface ocean and air CO_2 values can be used to constrain CO_2 fluxes in a similar fashion as heat and momentum fluxes (Edson et al., 2004). The MBL CO_2 measurements are part of a broader effort of greenhouse gas measurements over the ocean including nitrous oxide and methane in ICOS.

The network is focused on the infrastructure to deliver accurate pCO_2 data. It is envisioned that the JCOMM Observations Program Area (OPA) structure will facilitate the operational interactions with other networks. The interactions are largely synergistic, and include the needs for implementing SOCONET, and benefits of SOCONET to other efforts.

Efforts and Networks That Are of Direct Benefit to SOCONET

The surface ocean thermosalinograph (TSG) network and data management by the Global Ocean Surface Underway Data project, GOSUD provide sea surface temperature and salinity data. TSGs are integral support instruments for surface ocean CO_2 observations and interpretation, and are often critical for their transformation to OA parameters. All underway and mooring CO_2 systems have TSGs but these data do not undergo quality control as part of the pCO_2 data reduction. While TSG data are captured in the pCO_2 files, it is at lower temporal resolution congruent with the pCO_2 measurements. Interactions with JCOMM/SOT/SOOP should facilitate that the TSG data on SOOP-CO2 and Mooring-CO2 are quality controlled and served to the community. The quality control of salinity data would be coordinated through GOSUD. Automated routines for TSG data are available but access and flagging routines are cumbersome.

The Volunteer Observing Ship (VOS) Meteorological observations and moorings under the Data Buoy Cooperation Panel (DBCP) benefit SOCONET as barometric pressure is a key variable to calculate pCO_2 in air and water. These measurements are made routinely on VOS for weather applications, and barometers are calibrated by the national weather services. Wind speeds used to calculate air-sea CO_2 fluxes are generally obtained from remote sensing or numerical weather models but anemometer on ships or buoys are useful for comparison or validation of wind products.

Contributions of SOCONET to Other Research and Network Efforts

Measurements of pCO_{2a} from SOCONET platforms can be used to improve the NOAA/GMD MBL CO_2 reference product; to validate of MBL CO_2 in support of remote sensing (Chatterjee et al., 2017); and ground-based networks, such as TCCON (the Total Carbon Column Observing Network). An example of current satellite capacity to obtain synoptic global column XCO_2 based on the OCO2 mission values on global scales is provided in **Figure 8**.

The value of underway pCO_2 system MBL CO_2 measurements with inaccuracies of up to 0.2 ppm still needs to be fully investigated; although these data would not meet the WMO CCL compatibility goal of $+/-$ 0.1 ppm, but they still offer potential to be included in the collation/distribution efforts of the atmospheric measurement community because they help to fill gaps in the atmospheric measurement network. The World Data Centre for Greenhouse Gases (WDCGG), operated by the Japan Meteorological Agency (JMA) under GAW/WMO, and NOAA ObsPack products are two such atmospheric measurement community data distribution efforts that MBL CO_2 data from pCO_2 systems on ships could potentially contribute to. The atmospheric inverse modeling community as potential users of MBL CO_2, for example, those involved in the TransCom and IG3IS initiatives, is another way the underway pCO_2 community could forge and strengthen links with other scientists looking a similar carbon cycle issues from different angles.

The data from the SOCONET effort can be used to validate pCO_2 estimates from BGC (biogeochemical) Argo floats. The development of biogeochemical sensors for Argo floats will greatly enhance our observational capabilities of the ocean, including the possibility of using the pH data from Argo to calculate surface ocean pCO_2. The current estimated accuracy for pCO_{2w} values derived from pH is about 7 μatm (Williams et al., 2017; Gray et al., 2018). However, the pH sensors cannot be calibrated once deployed, and pCO_{2w} estimates need to be validated to evaluate how systematic errors evolve with time. This can be accomplished with ships in SOCONET. For example, cross-overs between SOCCOM BGC floats and the ARSV *Laurence M. Gould* have been evaluated by Fay et al. (2018). Strategies for targeting of BGC floats with SOCONET ships could enhance validation efforts by increasing the number and quality of cross-overs. As the reference network includes research ships that deploy the BGC Argo floats, co-located measurements are also possible at the site and time of deployment. A rapid return of quality-controlled data is desirable for this application.

Surface Ocean CO_2 NETwork could be used to build out of a BGC network in the essential ocean variable (EOV) framework. Inorganic carbon is an EOV and pCO_2 is a key component of the inorganic carbon system. Monitoring pCO_2 from surface platforms will provide key insights on ocean acidification. It is a core measurement that can be used in conjunction with other developing BGC observations to study biological productivity in the ocean. The SOCONET reference network and its infrastructure have the potential to be the backbone of the surface ocean BGC observing system.

OUTLOOK AND RECOMMENDATIONS

Surface Ocean CO_2 NETwork is a partnership of many investigators that have as major goal measuring surface ocean CO_2 and MBL CO_2 levels on an operational basis following agreed upon procedures. The accurate measurements will be disseminated within a year of measurement. Platform and instrument metadata tracking would occur in near-real time. The current list of platforms and participants that expressed interest in being part of SOCONET can be found at www.aoml.noaa.gov/ocd/gcc/SOCONET. The measurements are key inputs to products addressing important social, policy, and economic issues of our time as they pertain to marine health and anthropogenic carbon sequestration. The SOCONET activities are not the sole effort of most partners who are involved in a variety of related research activities. This will facilitate interactions with other networks and research efforts. While the surface ocean and MBL measurements are automated, the data reduction and quality control for the level of accuracy required for SOCONET are labor intensive, adding to the challenges of timeliness and cost of operation of the network. From an organizational perspective, securing and maintaining resources in these international distributed networks is critical, and means need to be explored to accomplish this. This holds true particularly for the communal aspects, including network design, data tracking, and coordination. A procedure of securing equitable national contributions must be developed for SOCONET (and many other network activities as described in this volume). Working through intergovernmental entities such as JCOMM and GOOS will be of benefit. SOCONET can serve as

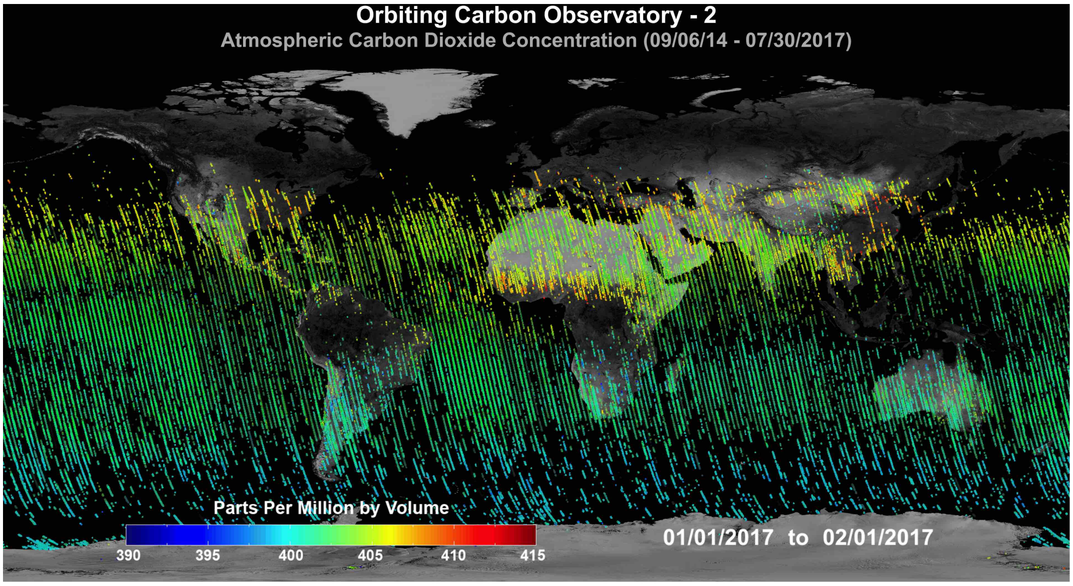


FIGURE 8 | Column xCO_2 measurement from the Observations from the Orbiting Carbon Observatory-2 (OCO-2) for January 2017. These data were produced by the OCO-2 project at the Jet Propulsion Laboratory, California Institute of Technology, and obtained from the OCO-2 data archive maintained at the NASA Goddard Earth Science Data and Information Services Center.

an example how networks will transition from platform-based to EOV-based entities addressing stakeholder needs.

The recommendations evolve around the establishment of the network for accurate pCO_{2w} and MBL CO_2 measurements following GOOS/JCOMM network principles that include utilizing the approaches of technical readiness level and addressing current impediments for execution. The following recommendations for implementing SOCONET and MBL measurements are the general steps necessary to develop and maintain a sustained network of surface ocean observations:

Resource Requirements

Determine the cost and agency contributions for a sustained reference network and develop strategies to maintain such a network including common operational facilities. Sustained support for technical coordination through JCOMMOPS needs to be sought.

Labeling of All Platforms in SOCONET

Labeling is a term used in ICOS referring to a station providing the required metadata and readiness of the measurements. For SOCONET the labeling and tracking of platforms would occur through JCOMMOPS.

Protocols for Quality Control and Verification of SOCONET Data

Surface Ocean CO_2 NETwork instruments should be operated with a means to verify quality though a series of steps including shoreside checks, side-by-side comparisons, crossover checks, traceable gas standards and periodic calibration or calibration checks of system components.

Network Performance Checks

The network performance would be evaluated based on number of platforms acquiring data, initial quality assessment, data loss and causes thereof, and network stability based on number of platforms and location of measurements. Implementing these checks will require creating a set of metrics based on the delivery surface ocean and MBL CO_2 data to specified accuracy and density.

MBL Air Measurements From SOCONET Platforms

Verify accuracy of current systems and determine protocols to determine quality of data including use of target gases and intercomparisons. Determine if accuracy meets community needs, and assess alternative arrangements such as different sampling frequency, sensors or stand-alone systems.

Utility of Measurements

Determine and track users and uses of measurements. This includes outreach and new applications focused on societal importance. In particular determine new customers of the reference data such as those who are involved in greenhouse gas verification schemes.

Surface Ocean CO_2 NETwork and associated MBL CO_2 measurements is an emerging network utilizing established instruments and platforms. It is focused on applying best practices for reference quality measurements, rapid data delivery, and platform tracking. The coordinated effort should aid development of timely and routine data products delivery in support of quantifying air-sea CO_2 fluxes, trends and variability in MBL and surface ocean pCO_2. It should lead to positive exposure and stability of funding for all the participants who rely on national resources for operation of their systems.

AUTHOR CONTRIBUTIONS

All authors listed have made direct and intellectual contributions to the work, and approved it for publication. RW and PP were the lead on the surface ocean and MBL components, respectively. MH performed a thorough proofreading of the galley proofs.

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The community white manuscript is the result of merging two submitted topics for the OceanObs'19: "establishing a global surface ocean CO_2 reference observing network", and "toward including atmospheric CO_2 data from the oceanic community into the global high-accuracy atmospheric CO_2 network of the surface ocean". The manuscript attempts to discuss the efforts as one entity from a scientific perspective but combining these operationally is an ongoing discussion and will depend, in part, as to what accuracy the MBL CO_2 values can be determined reliably from systems measuring pCO_{2w}. The conceptual development of a surface ocean CO_2 reference network, SOCONET, and associated marine boundary layer CO_2 measurements were aided by discussions at the 10th International Carbon Dioxide Conference (ICDC-10) and the 19th WMO/IAEA Meeting on Carbon Dioxide, Other Greenhouse Gases, and Related Measurement Techniques (GGMT-2017 (August 2017), and a dedicated workshop sponsored by the International Ocean Carbon Coordination Project (IOCCP) and the NOAA Ocean Observation and Monitoring Division in Portland, OR, United States (January 2018).

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2019.00400/full#supplementary-material

REFERENCES

Arora, V. K., Boer, G. J., Friedlingstein, P., Eby, M., Jones, C. D., Christian, J. R., et al. (2013). Carbon–concentration and carbon–climate feedbacks in CMIP5 earth system models. *J. Clim.* 26, 5289–5314. doi: 10.1175/jcli-d-12-00494.1

Babenhauserheide, A., Basu, S., Houweling, S., Peters, W., and Butz, A. A. (2015). Comparing the carbon tracker and TM5-4DVar data assimilation systems for CO_2 surface flux inversions. *Atmos. Chem. Phys.* 15, 9747–9763. doi: 10.5194/acp-15-9747-2015

Baer, D. S., Paul, J. B., Gupta, M., and O'Keefe, A. (2002). "Sensitive absorption measurements in the near-infrared region using off-axis integrated cavity output spectroscopy. In: Diode Lasers and Applications in Atmospheric Sensing," in *Proceedings of the Society of Photo-Optical Instrumentation Engineers* (SPIE), ed. A. Fried (Bellingham: Spie-Int Soc Optical Engineering).

Bakker, D. C. E., Pfeil, B., Landa, C. S., Metzl, N., Olsen, A., Smith, K., et al. (2016). A multi-decade record of high-quality fCO_2 data in version 3 of the surface ocean CO_2 Atlas (SOCAT). *Earth Syst. Sci. Data* 8, 383–413. doi: 10.5194/essd-8-382016

Bates, N. R., Astor, Y. M., Church, M. J., Currie, K. I, Dore, J. E., Gonzalez–Davila, M., et al. (2014). Changing ocean chemistry: a time–series view of ocean uptake of anthropogenic CO_2 and ocean acidification. *Oceanography* 27, 121–141. doi: 10.5670/oceanog.2014.03

Becker, M., Andersen, B., Fiedler, B., Fietzek, P., Körtzinger, A., Steinhoff, T., et al. (2012). Using cavity ringdown spectroscopy for continuous monitoring of $\delta^{13}C(CO_2)$ and fCO_2 in the surface ocean. *Limnol. Oceanogr. Methods* 10, 752–766. doi: 10.4319/lom.2012.10.752

Bender, M., Doney, S., Feely, R. A., Fung, I., Gruber, N., Harrison, D. E., et al. (2002). *A Large-Scale Carbon Observing Plan: in Situ Oceans and Atmosphere (LSCOP)*. Springfield: Nat. Tech. Info. Services.

Broquet, G., Chevallier, F., Bréon, F.-M., Kadygrov, N., Alemanno, M., Apadula, F., et al. (2013). Regional inversion of CO_2 ecosystem fluxes from atmospheric measurements: reliability of the uncertainty estimates. *Atmos. Chem. Phys.* 13, 9039–9056. doi: 10.5194/acp-13-9039-2013

Chatterjee, A., Gierach, M. M., Sutton, A. J., Feely, R. A., Crisp, D., Eldering, A., et al. (2017). Influence of El Niño on atmospheric CO_2 budget over the tropical Pacific Ocean: findings from NASA's OCO-2 mission. *Science* 358:6360. doi: 10.1126/science.aam5776

Cheng, L., Normandeau, C., Bowden, R., Doucett, R., Gallagher, B., Gillikin, D. P., et al. (2019). An international intercomparison of stable carbon isotope composition measurements of dissolved inorganic carbon in seawater. *Limnol. Oceanogr. Methods* 17, 200–209. doi: 10.1002/lom3.10300

Chevallier, F., Ciais, P., Conway, T. J., Aalto, T., Anderson, B. E., Bousquet, P., et al. (2010). CO_2 surface fluxes at grid point scale estimated from a global 21- year reanalysis of atmospheric measurements. *J. Geophys. Res.* 115:D21307. doi: 10.1029/2010JD013887

Colt, S. G., and Knapp, G. P. (2016). Economic effects of an ocean acidification catastrophe. *Am. Econom. Rev.* 106, 615–619. doi: 10.1257/aer.p20161105

Conway, T. J., Tans, P. P., Waterman, L. S., Thoning, K. W., Kitzis, D. R., Masarie, K. A., et al. (1994). Evidence for interannual variability of the carbon cycle from the NOAA/CMDL global air sampling network. *J. Geophys. Res.* 99, 22831–22855.

Crosson, E. R. (2008). A cavity ring-down analyzer for measuring atmospheric levels of methane, carbon dioxide, and water vapour. *Appl. Phys. B-Lasers Opt.* 92, 403–408. doi: 10.1007/s00340-008-3135-y

D'Maris, C., and Andrew, L. (2017). Carbon dioxide removal and the futures market. *Environ. Res. Lett.* 12:015003. doi: 10.1088/1748-9326/aa54e8

Edson, J. B., Zappa, C. J., Ware, J. A., McGillis, W. R., and Hare, J. E. (2004). Scalar flux profile relationships over the open ocean. *J. Geophys. Res.* 109:C08S09. doi: 10.1029/2003JC001960

El Yazidi, A., Ramonet, M., Ciais, P., Broquet, G., Pison, I., Abbaris, A., et al. (2018). Identification of spikes associated with local sources in continuous time series of atmospheric CO, CO_2 and CH4. *Atmos. Meas. Techn.* 11, 1599–1614. doi: 10.5194/amt-11-1599-2018

Esler, M. B., Griffith, D. W. T., Wilson, S. R., and Steele, L. P. (2000). Precision trace gas analysis by FT-IR spectroscopy. 1. Simultaneous analysis of CO_2, CH4, N_2O, and CO in air. *Anal. Chem.* 72, 206–215. doi: 10.1021/ac9905625

EW Team (2005). *Marine Boundary Layer Reference - NOAA Earth System Research*. Available at: https://www.esrl.noaa.gov/gmd/ccgg/mbl/ doi: 10.1021/ac9905625 (accessed September 25, 2018).

Fay, A. R., and McKinley, G. A. (2014). Global open-ocean biomes: mean and temporal variability. *Earth Syst. Sci. Data* 6, 273–284. doi: 10.5194/essd-6-273-2014

Fay, A. R., Lovenduski, N. S., McKinley, G. A., Munro, D. R., Sweeney, C., Gray, A., et al. (2018). Utilizing the drake passage time-series to understand variability and change in subpolar Southern Ocean pCO_2. *Biogeosciences* 15, 3841–3844. doi: 10.5194/bg-15-3841-2018

Field, C. B., Barros, V., Stocker, T. F., Dahe, Q., Mach, K. J., Plattner, G.-K., et al. (2011). *IPCC WGII/WGI Workshop on Impacts of Ocean Acidification on Marine Biology and Ecosystems*. Stanford CA: IPCC Working Group II Technical Support Unit, Carnegie Institution.

Frankignoulle, M., Canon, C., and Gattuso, J.-P. (1994). Marine calcification as a source of carbon dioxide: positive feedback of increasing atmospheric CO_2. *Limnol. Oceanogr.* 39, 458–462. doi: 10.4319/lo.1994.39.2.0458

Gaubert, B., Stephens, B. B., Basu, S., Chevallier, F., Deng, F., Eric, A., et al. (2019). Global atmospheric CO_2 inverse models converging on neutral tropical land exchange, but disagreeing on fossil fuel and atmospheric growth rate. *Biogeosciences* 16, 117–134. doi: 10.5194/bg-16-117-2019

González-Dávila, M., Santana-Casiano, J. M., and Machín, F. (2017). Changes in the partial pressure of carbon dioxide in the Mauritanian-Cap Vert upwelling region between 2005 and 2012. *Biogeosciences* 14:2017. doi: 10.5194/bg-14-3859-2017

Gray, A. R., Johnson, K. S., Bushinsky, S. M., Riser, S. C., Russell, J. L., Talley, L. D., et al. (2018). Autonomous biogeochemical floats detect significant carbon dioxide outgassing in the high-latitude Southern Ocean. *Geophys. Res. Lett.* 45, 9049–9057. doi: 10.1029/2018GL078013

Iida, Y., Kojima, A., Takatani, Y., Nakano, T., Sugimoto, Y., Midorikawa, T., et al. (2015). Trends in pCO_2 and sea–air CO_2 flux over the global open oceans for the last two decades. *J. Oceanogr*. 71:637. doi: 10.1007/s10872-015-0306-4

Jacobson, A. R., Mikaloff Fletcher, S. E., Gruber, N., Sarmiento, J. S., and Gloor, M. (2007). A joint atmosphere-ocean inversion for surface fluxes of carbon dioxide: 1. Methods and global- scale fluxes. *Glob. Biogeochem. Cycles* 21:GB1019. doi: 10.1029/2005GB002556

Jiang, L.-Q., Feely, R. A., Carter, B. R., Greeley, D., and Arzayus, K. M. (2015). Climatological distribution of aragonite saturation state in the global oceans. *Glob. Biogeochem. Cycles* 29, 1656–1673. doi: 10.1002/2015GB005198

Kamenkovich, I., Haza, A., Gray, A. R., Dufour, C. O., and Garraffo, Z. (2017). Observing system simulation experiments for an array of autonomous biogeochemical profiling floats in the Southern Ocean. *J. Geophys. Res. Oceans* 122, 7595–7611. doi: 10.1002/2017JC012819

Kang, J. S., Kalnay, E., Liu, J. J., Fung, I., Miyoshi, T., and Ide, K. (2011). "Variable localization" in an ensemble Kalman filter: Application to the carbon cycle data assimilation. *J. Geophys. Res. Atmos.* 116:D09110. doi: 10.1029/2010jd014673

Keeling, C. D. (1958). The concentration and isotopic abundances of atmospheric carbon dioxide in rural areas. *Geochim. Cosmochim. Acta* 13, 322–334. doi: 10.1016/0016-7037(58)90033-4

Keeling, C. D. (1965). Carbon dioxide in surface waters of the Pacific Ocean 2. Calculation of the exchange with the atmosphere. *J. Geophys. Res.* 70, 6099–6102. doi: 10.1029/jz070i024p06099

Keeling, R. F. (2008). Atmospheric science: recording earth's vital signs. *Science* 319, 1771–1772. doi: 10.1126/science.1156761

Kozlova, E. A., and Manning, A. C. (2009). Methodology and calibration for continuous measurements of biogeochemical trace gas and O_2 concentrations from a 300-m tall tower in central Siberia. *Atmos. Meas. Tech.* 2, 205–220. doi: 10.5194/amt-2-205-2009

Landschützer, P., Gruber, N., Bakker, D. C. E., Schuster, U., Nakaoka, S., Payne, M. R., et al. (2013). A neural network-based estimate of the seasonal to inter-annual variability of the Atlantic Ocean carbon sink. *Biogeosciences* 10, 7793–7815. doi: 10.5194/bg-10-7793-2013

Landschützer, P., Gruber, N., Bakker, D. C. E., and Schuster, U. (2014). Recent variability of the global ocean carbon sink. *Glob. Biogeochem. Cycles* 28, 927–949. doi: 10.1002/2014gb004853

Laurent, O. (2017). *ICOS Atmospheric Station Specifications. Version 1.3*. Available at: https://icos-atc.lsce.ipsl.fr/filebrowser/download/69422 (accessed July, 2019).

Lauvset, S. K., Gruber, N., Landschützer, P., Olsen, A., and Tjiputra, J. (2015). Trends and drivers in global surface ocean pH over the past 3 decades. *Biogeosci. Discuss.* 12, 1285–1298. doi: 10.5194/bg-12-1285-2015

Le Quéré, C., Andrew, R. M., Friedlingstein, P., Sitch, S., Hauck, J., Pongratz, J., et al. (2018). Global carbon budget 2018. *Earth Syst. Sci. Data Discuss.* 2018, 1–3. doi: 10.5194/essd-2018-120

Lee, K., Wanninkhof, R., Takahashi, T., Doney, S., and Feely, R. A. (1998). Low interannual variability in recent oceanic uptake of atmospheric carbon dioxide. *Nature* 396, 155–159. doi: 10.1038/24139

Li, Z., Adamec, D., Takahashi, T., and Sutherland, S. C. (2005). Global autocorrelation scales of the partial pressure of oceanic CO_2. *J. Geophys. Res.* 110:C08002. doi: 10.1029/2004JC002723

Majkut, J. D., Carter, B. R., Frölicher, T. L., Dufour, C. O., Rodgers, K. B., and Sarmiento, J. L. (2014). An observing system simulation for Southern Ocean carbon dioxide uptake. *Philos. Trans. R. Soc. A* 372:20130046. doi: 10.1098/rsta.2013.0046

Merlivat, L., Boutin, J., and d'Ovidio, F. (2015). Carbon, oxygen and biological productivity in the Southern Ocean in and out the Kerguelen plume: CARIOCA drifter results. *Biogeosci. Discuss.* 12, 3513–3524. doi: 10.5194/bg-12-3513-2015

Monteiro, P., Schuster, U., Hood, M., Lenton, A., Metzl, N., Olsen, A., et al. (2010). "A global sea surface carbon observing system: Assessment of changing sea surface CO_2 and air-sea CO_2 fluxes," in *Sustained Ocean Observations and Information for Society*, Vol. 2, eds J. Hall and D. Stammer (Venice: ESA Publication).

Müller, J. D., Schneider, B., and Rehder, G. (2016). Long-term alkalinity trends in the Baltic Sea and their implications for CO_2-induced acidification. *Limnol. Oceanogr.* 61, 1984–2002. doi: 10.1002/lno.10349

Northcott, D., Sevadjian, J., Sancho-Gallegos, D. A., Wahl, C., Friederich, J., and Chavez, F. P. (2019). Impacts of urban carbon dioxide emissions on sea-air flux and ocean acidification in nearshore waters. *PLoS One* 6:115. doi: 10.1371/journal.pone.0214403

National Center for Atmospheric Research Staff [NCAR] (ed.) (2013). *The Climate Data Guide: Taylor Diagrams*. Available at: http//climatedataguide.ucar.(edu)/climate-data-tools-and-analysis/taylor-diagrams (accessed July 23, 2013).

Oliver, M. J., and Irwin, A. J. (2008). Objective global ocean biogeographic provinces. *Geophys. Res. Let.* 35:L15601. doi: 10.1029/2008GL034238

Park, G.-H., Wanninkhof, R., Doney, S. C., Takahashi, T., Richard, K. L., Feely, A., et al. (2010). Variability of global net sea-air CO_2 fluxes over the last three decades using empirical relationships. *Tellus* 62B, 352–368. doi: 10.1111/j.1600-0889.2010.00498.x

Peters, W., Jacobson, A. R., Sweeney, C., Andrews, A. E., Conway, T. J., Masarie, K., et al. (2007). An atmospheric perspective on North American carbon dioxide exchange: carbonTracker. *Proc. Natl. Acad. Sci. U.S.A.* 104, 18925–18930. doi: 10.1073/pnas.0708986104

Peters, G. P., Le Quéré, C., Andrew, R. M., Canadell, J. G., Friedlingstein, P., Ilyina, T., et al. (2017). Towards real-time verification of CO_2 emissions. *Nat. Clim. Change* 7, 848–850. doi: 10.1038/s41558-017-0013-9

Pfeil, B., Olsen, A., Bakker, D. C. E., Hankin, S., Koyuk, H., Kozyr, A., et al. (2013). A uniform, quality controlled Surface Ocean CO_2 Atlas (SOCAT). *Earth Syst. Sci. Data* 5, 125–143.

Pickers, P. A. (2016). *New Applications of Continuous Atmospheric O_2 Measurements: Meridional Transects Across the Atlantic Ocean, and*

Improved Quantification of Fossil Fuel- Derived CO_2. Ph.D. thesis, School of Environmental Sciences, University of East Anglia, Norwich. Available at: http://cramlab.uea.ac.uk/Documents/Pickers_Penelope_PhD_Thesis_2016.pdf

Pickers, P. A., Manning, A. C., Sturges, W. T., Quéré, C., Fletcher, S. E. M., Wilson, P. A., et al. (2017). In situ measurements of atmospheric O_2 and CO_2 reveal an unexpected O_2 signal over the tropical Atlantic Ocean. *Glob. Biogeochem. Cycles* 31, 1289–1305. doi: 10.1002/2017gb005631

Pierrot, D., Neil, C., Sullivan, K., Castle, R., Wanninkhof, R., Lueger, H., et al. (2009). Recommendations for autonomous underway pCO_2 measuring systems and data reduction routines. *Deep Sea Res. II* 56, 512–522. doi: 10.1016/j.dsr2.2008.12.005

Revelle, R., and Suess, H. (1957). Carbon dioxide exchange between atmosphere and ocean and the question of an increase of atmospheric CO_2 during the past decades. *Tellus* 9, 18–27. doi: 10.3402/tellusa.v9i1.9075

Rödenbeck, C., Conway, T. J., and Langenfelds, R. L. (2006). The effect of systematic measurement errors on atmospheric CO_2 inversions: a quantitative assessment. *Atmos. Chem. Phys.* 6, 149–161. doi: 10.5194/acp-6-149-2006

Rödenbeck, C. D., Bakker, C. E., Gruber, N., Iida, Y., Jacobson, A. R., Jones, S., et al. (2015). Data-based estimates of the ocean carbon sink variability –first results of the Surface Ocean pCO_2 Mapping intercomparison (SOCOM). *Biogeosciences* 12, 7251–7278. doi: 10.5194/bg-12-7251-2015

Rodgers, C. D. (2000). *Inverse Methods for Atmospheric Sounding*. Tokyo: World Scientific.

Salisbury, J., Vandemark, D., Jönsson, B., Balch, W., Chakraborty, S., Lohrenz, S., et al. (2015). How can present and future satellite missions support scientific studies that address ocean acidification? *Oceanography* 28, 108–121. doi: 10.5670/oceanog.2015.35

Schneider, B., and Müller, J. D. (2018). *Biogeochemical Transformations in the Baltic Sea: Observations Through Carbon Dioxide Glasses*. Berlin: Springer.

Schuster, U., and Watson, A. J. (2007). A variable and decreasing sink for atmospheric CO_2 in the North Atlantic. *J. Geophys. Res.* 112:C11006.

Shutler, J. D., Wanninkhof, R., Nightingale, P. D., Woolf, D. K., Bakker, D. C. E., and Watson, A. J., et al. (2019). Rediscovering the ocean carbon sink: satellites will enable us to watch the global oceans breathe. *Front. Ecol. Environ.*

Sutton, A. J., Sabine, C. L., Maenner-Jones, S., Lawrence-Slavas, N., Meinig, C., Feely, R. A., et al. (2014). A high-frequency atmospheric and seawater pCO_2 data set from 14 open-ocean sites using a moored autonomous system. *Earth Syst. Sci. Data* 6, 353–366. doi: 10.5194/essd-6-353-2014

Sutton, A. J., Feely, R. A., Maenner-Jones, S., Musielwicz, S., Osborne, J., Dietrich, C., et al. (2019). Autonomous seawater pCO_2 and pH time series from 40 surface buoys and the emergence of anthropogenic trends. *Earth Syst. Sci. Data* 11, 421–439. doi: 10.5194/essd-11-421-2019

Takahashi, T. (1961). Carbon dioxide in the atmosphere and in Atlantic Ocean water. *J. Geophys. Res.* 66, 477–494. doi: 10.1029/JZ066i002p00477

Takahashi, T., Steawart, C. S., Rik, W., Colm, S., Richard, A. F., David, W. C., et al. (2009). Climatological mean and decadal change in surface ocean pCO_2, and net sea-air CO_2 flux over the global oceans. *Deep Sea Res. II* 2009, 554–577. doi: 10.1016/j.dsr2.2008.12.009

Takahashi, T., Sutherland, S. C., Chipman, D. W., Goddard, J. C., Ho, C., Newberger, T., et al. (2014). Climatological distributions of pH, pCO_2, total CO_2, alkalinity, and $CaCO_3$ saturation in the global surface ocean, and temporal changes at selected locations. *Mar. Chem.* 164, 95–125. doi: 10.1016/j.marchem.2014.06.004

Taylor, K. E. (2001). Summarizing multiple aspects of model performance in a single diagram. *J. Geophys. Res.* 106, 7183–7192. doi: 10.1029/2000JD900719

Wanninkhof, R., Barbero Pierrot, D., Shuster, U., Tedesco, K., Sutton, A., and Telszewski, M. (2018). *A Surface Ocean CO_2 Observing Network, SOCONET, Prospectus*. Available at: www.aoml.noaa.gov/ocd/gcc/SOCONET/SOCONET_prospectus.pdf (asccessed February 12, 2019).

Wanninkhof, R. (2014). Relationship between wind speed and gas exchange over the ocean revisited. *Limnol. Oceanogr. Methods* 12, 351–362. doi: 10.4319/lom.2014.12.351

Wanninkhof, R., Feely, R., Sutton, A., Sabine, C., Tedesco, K., Gruber, N., et al. (2012). "An integrated ocean carbon observing system (IOCOS)," in *Proceedings, U.S. Integrated Ocean Observing System (IOOS) Summit, Interagency Ocean Observation Committee (IOOC)*. Herndon, VA (accessed November 13–16, 2012).

Weart, S. R. (2008). *The Discovery of Global Warming, Revised and Expanded Edition*. Cambridge: Harvard University Press.

Williams, N. L., Juranek, L. W., Feely, R. A., Johnson, K. S., Sarmiento, J. L., Talley, L. D., et al. (2017). Calculating surface ocean pCO_2 from biogeochemical Argo floats equipped with pH: An uncertainty analysis. *Glob. Biogeochem. Cycles* 31, 591–604. doi: 10.1002/2016GB005541

WMO/GAW Report 229 (2016). *Report from the 18th WMO/IAEA Meeting on Carbon Dioxide, Other Greenhouse Gases and Related Measurement Techniques (GGMT-2015)*. La Jolla, CA: WMO.

Zappa, C. J., Asher, W. E., Jessup, A. T., Klinke, J., and Long, S. R. (2004). Microbreaking and the enhancement of air-water transfer velocity. *J. Geophys. Res.* 109:C08S16. doi: 10.1029/2003JC001897

Zellweger, C., Emmenegger, L., Firdaus, M., Hatakka, J., and Heimann, M. (2016). Assessment of recent advances in measurement techniques for atmospheric carbon dioxide and methane observations. *Atmos. Meas. Tech.* 9, 4737–4757. doi: 10.5194/amt-9-4737-2016

Zeng, J., Matsunaga, T., Saigusa, N., Shira, T., Nakaoka, S.-I., and Tan, Z.-H. (2017). Technical note: Evaluation of three machine learning models for surface ocean CO_2 mapping. *Ocean Sci.* 13, 303–313. doi: 10.5194/os-13-303-2017

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APPENDIX A: OCEAN ACIDIFICATION AND PCO_2

A direct impact of increasing pCO_2 levels in the ocean is the phenomenon of ocean acidification. While the definitions of OA vary to some extent most are in line with the following: "Ocean acidification refers to a reduction in the pH of the ocean over an extended period of time, typically decades or longer, which is caused primarily by uptake of carbon dioxide (CO_2) from the atmosphere." (Field et al., 2011). With increasing emphasis on changes in ocean inorganic carbon chemistry in addition to pH decrease, the definition is broadened to: "reduction of seawater pH and changes ocean chemistry that are collectively referred to as ocean acidification."

Surface Ocean CO_2 NETwork thus addresses the key forcing components of OA involving the uptake of anthropogenic CO_2 and changing surface ocean CO_2. There is a strong correlation between pCO_2 and pH as can be seen from the hydration reaction and dissociation of CO_2 summarized by the chemical equation:

$$CO_2 + H_2O = H_2CO_3 = H^+ + HCO_3^- = 2H^+ + CO_3^{2-} \quad \text{(A1)}$$

The changes in inorganic carbon speciation can impact the biogeochemical and biological responses. In particular, increasing CO_2 concentrations lower carbonate ion concentrations through the major net buffering reaction in the oceanic inorganic carbon system that can be summarized as:

$$CO_2 + CO_3^{2-} + H_2O = 2\ HCO_3^- \quad \text{(A2)}$$

An example of the correlation between pCO_2 and pH for surface water is shown in **Supplementary Figure S1** using surface ocean measurements from a GO-SHIP cruise P18 in the SE Pacific. The strong correspondence is apparent, and deviations from a singular relationship are due to differences in the buffering of the seawater that will impact the equilibria in A1 and A2.

Increasing CO_2 leads to a decrease in carbonate levels and resulting decrease of calcium carbonate saturation state (Bates et al., 2014). This is of concern for calcifying organisms that are abundant in the ocean. The biological production of corals, as well as calcifying phytoplankton and zooplankton will be inhibited or slowed. The dissolution of biotic and abiotic calcium carbonate in the water column and the ocean floor will be enhanced.

Species containing aragonite, and meta-stable forms of calcium carbonate produced by corals and plankton, such as pteropods will be particularly susceptible to a reduction of $CO_3{}^{2-}$ in seawater.

Ocean acidification also impacts organisms that do not fix calcium carbonate. Increasing seawater CO_2 levels and lower pH can weaken metabolic processes for organisms, from feeding to respiration to reproduction and change the chemical speciation of trace metals essential for their needs. While predicting the precise response of ocean ecosystems is challenging for scenarios of increased CO_2 levels, it is likely the ecosystems will be less productive, less diverse and less resilient. In addition, the synergistic impacts of other climate and human impacts on the ocean, including ocean warming and de-oxygenation, will exacerbate the impacts of elevated CO_2 levels and associated acidification. SOCONET data will provide critical input on the trends of the major factors influencing OA and air-sea CO_2 fluxes, and resulting decreases in pH and carbonate levels.

frontiers in Marine Science

REVIEW
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Observational Needs for Improving Ocean and Coupled Reanalysis, S2S Prediction, and Decadal Prediction

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Developments in observing system technologies and ocean data assimilation (DA) are symbiotic. New observation types lead to new DA methods and new DA methods, such as coupled DA, can change the value of existing observations or indicate where new observations can have greater utility for monitoring and prediction. Practitioners of DA are encouraged to make better use of observations that are already available, for example, taking advantage of strongly coupled DA so that ocean observations can be used to improve atmospheric analyses and vice versa. Ocean reanalyses are useful for the analysis of climate as well as the initialization of operational long-range prediction models. There are many remaining challenges for ocean reanalyses due to biases and abrupt changes in the ocean-observing system throughout its history, the presence of biases and drifts in models, and the simplifying assumptions made in DA solution methods. From a governance point of view, more support is needed to bring the ocean-observing and DA communities together. For prediction applications, there is wide agreement that protocols are needed for rapid communication of ocean-observing data on numerical weather prediction (NWP) timescales. There is potential for new observation types to enhance the observing system by supporting prediction on multiple timescales, ranging from the typical timescale of NWP, covering hours to weeks, out to multiple decades. Better communication between DA and observation communities is encouraged in order to allow operational prediction centers the ability to provide guidance for the design of a sustained and adaptive observing network.

Keywords: data assimilation, reanalysis, coupled data assimilation, S2S prediction, decadal prediction, ocean observation network, ocean data assimilation, ocean reanalysis

INTRODUCTION

Sustained high-quality observations are essential for improving our understanding of the ocean and its interactions with the atmosphere and the overall Earth system. An important tool to study the Earth system is the production of historically accurate four-dimensional reconstructions of quantities that characterize the ocean state (such as temperature, salinity, and currents). Mathematical methods from the field of Data Assimilation (DA) allow information provided from observations to be propagated in time and space to unobserved areas using the dynamical and physical constraints imposed by numerical models. When these methods are applied to form the aforementioned historical reconstructions, this procedure is called a retrospective analysis, or "reanalysis" (Kalnay et al., 1996; Dee et al., 2014). In addition to aiding in the study of the ocean itself, such reanalyses can also be used to initialize the ocean component of coupled Earth system models in order to produce long-term forecasts that may provide guidance from a few weeks out to a decade or longer (Meehl et al., 2014; Balmaseda, 2017). Here, we review the current state-of-the-art of DA applied to the ocean and collectively look forward over the next decade to make our own predictions about what kind of complementary *in situ* and satellite observations will be required to advance reanalysis and prediction, address end-user engagement, identify opportunities for integration, and connect to many of the themes of OceanObs'19.

METHODOLOGICAL DEVELOPMENTS IN OCEAN DATA ASSIMILATION

Data assimilation is essentially an automation of the scientific method. A hypothesis is made and encoded in a numerical model. This model is then used to make predictions that can be tested against new observations. Prediction accuracy is then examined and provided as feedback to modify the model and methods, and the process repeats. The development and application of DA serves fundamental Earth science goals such as to: (1) fill gaps between sparse measurements to form a complete picture of the Earth system, (2) utilize the observing network to initialize forecast models, (3) characterize errors in the modeling and observing systems, and (4) identify areas of high uncertainty where observations can illuminate poorly understood phenomena, help target observing campaigns, and improve numerical models and forecasts. Here, we address the current state-of-the-art and limitations of ocean and coupled DA and propose paths forward.

CONNECTING OCEAN DATA ASSIMILATION WITH OCEAN OBSERVING EFFORTS

Although the growing constellation of satellite observing platforms continues to provide a much more coherent view of the ocean surface, there are limitations that remain in the integrated ocean-observing system that prevent the accurate estimation of the full state of the ocean based on observations alone. *In situ* measurements are quite sparse, while small-scale processes important to air-sea interaction and the deep ocean remain largely unobserved. In order to acquire a complete picture of the ocean state while appropriately characterizing our uncertainty of this picture, the gaps in coverage must be bridged in space and time using rigorous mathematical methods. This is a primary activity of the DA community and requires close collaborations between theorists in academia and practitioners at operational centers.

Ocean DA has become routine practice at many operational prediction centers, both for ocean forecasting and for initializing coupled Earth system models (Edwards et al., 2015; Martin et al., 2015). The regular application of ocean DA either through operational forecasts or using retrospective analyses (reanalyses) is valuable for assessing the completeness and accuracy of the ocean-observing system. A variety of tools are available to assess the value of specific observing platforms, some that follow the methodologies of Observing System Experiments (OSEs) and Observing System Simulation Experiments (OSSEs), or Optimal Experimental Design (OED), while others are linked to the DA cycle itself, such as Forecast Sensitivity to Observation Impacts (FSOI) and estimating the effective degrees of freedom of the observing system (e.g., Oke et al., 2015a,b).

Advances in DA methods have been and will continue to be driven by new observing technologies. We mention two notable features of upcoming observing technologies that deserve attention. First, amongst recent and planned satellite missions are increasingly high-resolution datasets covering the ocean surface. The development of instrumentation such as VIIRS, SLSTR on board Sentinel-3 (A and B), and platforms such as the Surface Water and Ocean Topography (SWOT) mission indicate there will be large volumes of data available for assimilation.

At present, the fidelity of these data products is far higher than many operational ocean models are capable of resolving. Ocean DA faces a challenge due to computational limitations: there is a need to either increase the resolution of ocean models in order to take full advantage of new data sources using conventional DA approaches or design new methods to extract more information from these observations without resorting to high-resolution modeling (e.g., by using machine learning methods applied to high-resolution observations to produce dynamic parameterizations at the subgrid-scale – see for example Bolton and Zanna, 2019). The accurate specification of observation error correlations becomes more important as higher resolutions are used (e.g., Mazloff et al., 2018), making it more difficult to accurately assimilate new higher resolution observations.

Amongst *in situ* observing systems, there is a trend toward mobile and adaptive platforms and new DA methods will be needed to use the full breadth of information provided by these platforms. As technology improves, there is also an opportunity to explore potential feedback between operational ocean DA systems and observing system guidance in near real-time that redirects the observing system to increase sampling in areas where the forecasts have greatest sensitivity. Ocean-observing technologies in the form of gliders, autonomous underwater vehicles, high-frequency radars, profiling floats, drifters, tagged marine mammals (and other pelagic apex predators), and acoustic instruments continue to undergo rapid development, and data volumes from these platforms are growing rapidly, particularly in coastal regions. Quality assurance and quality control (QA/QC) protocols are necessary, especially for new types of observations. Operational centers should improve their capability to provide feedback in near real-time regarding the QC classifications of individual observations based on forecasts made using those observations.

From a fundamental standpoint, most of the approaches used for characterizing uncertainty in Ocean DA methods are predicated on the principles of Bayes' theorem (Hoteit et al., 2018). A common assumption is that errors are Gaussian-distributed and that the time evolution of the errors is linear. As such, there are common limitations to all currently used DA methods and a primary goal for improving the accuracy and applicability of DA in the coming decade will be to relax these limiting constraints (see Martin et al., 2019; Moore et al., 2019, this issue). This has relevance to future ocean-observing system design, as it may change requirements on the observing system either to test and design new methods or to take advantage of new capabilities afforded by the methods.

In recent years, the Global Ocean Data Assimilation Experiment (GODAE) and its offshoot, GODAE OceanView (GOV) have been active in galvanizing ocean DA activities by providing a platform for promoting ocean DA and forging international collaborations (Bell et al., 2015). These activities will continue under the new guise of OceanPredict. Going forward, we recommend that this activity expand to further interface with the academic and operational ocean-observing, ocean modeling, and ocean DA communities.

THE ADVENT OF COUPLED DATA ASSIMILATION

The components of the Earth system have traditionally been analyzed independently. However, modeling improvements and increases in computing power are now enabling the analysis of the Earth system as a whole (Saha et al., 2010, 2014; Lea et al., 2015). Observation-model synthesis activities that incorporate observational data into coupled Earth system models have led to the emergence of a new research area called Coupled Data Assimilation (CDA; Penny et al., 2017). While traditional methods have generally focused on a single scale of motion within any given DA system, an essential characteristic of CDA is the need to account for the multiple spatiotemporal scales present in the error dynamics of the coupled system. The most basic application of DA to coupled models has been the application of legacy DA systems to each component separately, which is called weakly coupled data assimilation (WCDA). In order to allow any observation to directly affect the analysis of multiple model components across their interface, the DA itself must also be coupled; this is called strongly coupled data assimilation (SCDA). For most modern DA methods, SCDA requires that the forecast error covariance matrix be produced for the coupled state. Efforts are underway to develop effective approaches for SCDA, though additional work is still needed to understand the complexities of this problem (Penny et al., 2019).

By isolating systematic errors in prediction systems, CDA may help identify new transformative directions in ocean-observing strategies targeted at eliminating these errors. Because CDA allows ocean observations to directly inform atmospheric state estimates and vice versa (Sluka et al., 2016; Sluka, 2018), the relevance of existing observations for state estimation and prediction must be clarified as the ocean-observing network evolves. CDA developments involve a necessary reevaluation of requirements for ocean-observing capabilities, either by reducing the presence of redundant information or by using such redundant information to calibrate multiple observing platforms. CDA can effectively leverage multidisciplinary, sustained, collocated observations, and may require more information in new geographic locations, or of new previously unmeasured quantities, to better understand the structure of the cross-domain error covariance. Over the next decade, those designing components of the Earth-observing system should pay close attention to developments in CDA.

Operational centers are now developing CDA methods for NWP and reanalysis applications that include components such as the ocean, sea ice, land, and atmosphere (Brassington et al., 2015). One of the original motivations for improving CDA methods was to ensure consistency between the different components of the Earth system. The use of coupled Earth system models for operational prediction provides the potential to produce forecasts that target multiple prediction timescales. At NWP timescales, the diurnal cycle has a large influence on coupled processes in the boundary layers of the atmosphere and ocean. Mesoscale interactions between sea surface temperature (SST) fronts and near-surface winds (Chelton and Xie, 2010) may have significance to winds throughout the troposphere. Potential sources of predictability for Subseasonal-to-Seasonal (S2S) timescales include establishing teleconnections associated with the Madden–Julian oscillation (MJO), the evolution of the El-Niño Southern Oscillation (ENSO), soil moisture, snow cover and sea ice, stratosphere–troposphere interactions, upper ocean conditions, and tropical-extratropical teleconnections (Vitart et al., 2015). At decadal prediction timescales, accounting for coupled oscillations such as the Atlantic Multidecadal Oscillation (AMO) and the Pacific Decadal Oscillation (PDO) (d'Orgeville and Peltier, 2007) may be of greater importance for CDA.

Beyond coupled atmosphere-ocean interactions, the application of CDA is also important to better understand other coupled processes in more detail. For example, DA in coupled ocean-sea ice models (Fenty and Heimbach, 2013; Bertino and Holland, 2017; Kimmritz et al., 2018) and coupled physical-biogeochemical models (Brasseur et al., 2009; Song et al., 2016; Verdy and Mazloff, 2017) at both regional and global scales are currently active areas of research, driven by improvements in remote-sensing observing platforms (e.g., sea ice concentration and thickness and ocean color) or new capabilities (e.g., biogeochemical Argo floats and airborne hyperspectral imagers). There have been few studies to date exploring DA applied to coupled land-ocean processes.

Focus on biological activity highlights the importance of physical variables often ignored in conventional ocean DA, such as upper-ocean vertical fluxes (Brasseur et al., 2009). Large-scale assimilation of marine biogeochemistry is limited by the lack of regular observations. The only routine observations with global coverage are satellite ocean color (Ford and Barciela, 2017). Existing DA efforts typically focus on generating products based purely on biogeochemical measurements independently of physical oceanographic measurements (e.g., Ciavatta et al., 2016; Gregg et al., 2017). As CDA begins to mature, it would be highly beneficial for the physical oceanographic reanalysis and ocean biogeochemical reanalysis efforts to start integrating with one another (Rosso et al., 2017). Early interest in moving in this direction has been indicated, for example, by Perruche et al. (2017) as part of the ERA-CLIM2 project. Regional ocean analyses are being used to predict Harmful Algal Blooms (HABs; Anderson et al., 2016), to understand economically important marine ecosystems (e.g., Schroeder et al., 2014, 2017) with a view to management, and to understand the migration habits of endangered marine species (e.g., Becker et al., 2016), and it is expected that these applications will be enhanced with CDA.

To date, ECMWF has one of the more mature efforts developing a CDA system. An implicit coupling approach has been implemented in their CERA system, where the atmospheric 4D-Var and oceanic 3D-Var DA systems are synchronized using multiple outer iterations in the incremental variational formulation. This outer-loop coupling system is an approximation of a fully coupled 4D-Var system that tries to find an approximation to the same optimal solution by setting the coupled adjoint model and the cross-domain error covariance at the initial time of the assimilation window to zero (Laloyaux et al., 2018b). It takes between 6 and 12 h for the outer loop coupling to synchronize the coupled increments (Laloyaux et al., 2018a). This finding suggests that a long assimilation window (at least 12 h) is necessary for CERA to be an effective strategy for CDA. The outer-loop coupling employed by the CERA system could in principle be augmented by both the specification of the initial time coupled covariances and coupled adjoint. Such an approach could mitigate problems in cases where the coupled model is not able to synchronize the unbalanced increments that arise because the assimilation window is too short, the observations are inconsistent due to biases present in the observing platforms, or systematic modeling errors prevent agreement across the interface.

AN EXAMPLE APPLICATION OF CDA: THE DIRECT ASSIMILATION OF SATELLITE RADIANCES FOR ESTIMATING SST

The air-sea interface is one of the prime focus areas for early explorations of CDA. In addition to requiring a rethinking of DA algorithms and solution approaches, CDA affords the opportunity to improve the methods used to map the modeled state to a simulated "model equivalent" for each observation that can then be compared directly with observations. One of the most obvious places to start is improving the inputs provided to radiative transfer models. CDA provides a new capability to assimilate observed brightness temperature (BT) instead of relying on retrieval products such as proxy measurements for SST.

Current state-of-the-art coupled forecasting systems do not analyze interface states such as SST, sea surface salinity (SSS), or sea ice in a self-consistent manner. For example, many atmospheric and oceanic DA systems typically nudge toward SST retrieval products. However, this approach typically ignores caveats in the empirical methods used to convert satellite-measured radiances into SST retrieval data products (Donlon et al., 2007). Among the most serious are errors in model calibration at high latitudes as well as challenges in using skin SST estimates to constrain bulk temperature (Donlon et al., 2002). Diurnal variations of SST and near-surface cooling in the microlayer are processes that are well observed and studied (Kawai and Wada, 2007) but not very well represented in coupled atmosphere- ocean general circulation models (Brunke et al., 2008), in which reproducing SST variability remains a challenge (Lea et al., 2015).

There are numerous definitions for SST; for example, see Figure 1 of Donlon et al. (2007) or definitions established by the Group for High Resolution Sea Surface Temperature (GHRSST). Some of these definitions are conceptual (e.g., the interface SST) while others are derived from the method of measurement (e.g., infrared vs. microwave). Satellites have provided continuous infrared observations that sample in the upper 10–20 μm (the skin temperature) since the early 1980s and microwave observations (spatially less accurate than infrared, but insensitive to cloud cover and aerosols) that observe the upper few millimeters (the subskin temperature) since the late-1990s (Reynolds et al., 2007). *In situ* measurements of SST are sparser and typically comprised of top-level (1–2 m) moored buoys, drifting buoys (about 20–30 cm), and ship intake measurements (Castro et al., 2012; Legler et al., 2015) that are known to have large errors (Folland and Parker, 1995; Kennedy, 2014).

Satellite-based measurements of SST are inherently coupled due to influences from not only the sea surface but also the full atmospheric column above it. The measured SST is highly influenced by both atmosphere and ocean boundary layers as well as the strength of upward longwave radiation and turbulent heat flux exchanges. To avoid dealing with the complex calibration issues associated with satellite radiances, current prototype CDA systems typically rely on SST data products produced by specialists and assimilate either along-track (L2) SST estimates or gridded (L3 or L4) SST products such as Pathfinder (Casey et al., 2010), OSTIA (Stark et al., 2007), or ACSPO (Ignatov et al., 2016). See Martin et al. (2012) for a review of available L3 and L4 SST products. One of the main recommendations of a recent ECMWF workshop (Balmaseda et al., 2018) was to directly assimilate satellite radiances to constrain SST and sea ice, just as is done in NWP for atmospheric quantities. CDA offers an opportunity to treat the interfaces within the coupled model in a self-consistent manner, particularly when the forward model that is used to evaluate the "model equivalent" to the observation, $H(\boldsymbol{x})$, depends on state information from multiple domains.

Both the NASA Global Modeling and Assimilation Office (GMAO) (Akella et al., 2017) and the National Oceanographic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction (NCEP) Environmental Modeling Center (EMC) (Derber and Li, 2018) have already implemented methods to directly assimilate radiances in order to compute SST analyses. The NASA GMAO procedure followed Takaya et al. (2010) allows the SST diurnal cycle to be resolved in the model, which provides a near-surface temperature profile as a function of depth. Using the forecasted SST along with the forecasted atmospheric state as inputs to the radiative transfer model, the resulting forecast BT can be compared with observed BT. The difference between observed and forecasted BT is used by the DA method to form a consistent analysis of the combined atmospheric state and SST. In order to effectively constrain SST, observations that are sensitive to SST, such as infrared satellite radiance measurements onboard operational polar orbiting satellites, were added to the observing system (see Akella et al., 2017 for details and Gentemann and Akella, 2018 for a comparison/evaluation of their results with other diurnal-SST retrievals). The capability to assimilate satellite radiances in coupled forecasting systems has improved the predictability of the GMAO system, most notably near the surface. The BTs are atmospheric column-weighted measurements. Because infrared satellite measurements are sensitive to water vapor, improved resolution and assimilation of SST-sensitive BTs translated into improved observational innovation statistics for many satellite channels that contain information about tropospheric temperature and water vapor.

The advantages of combining infrared and microwave radiometric measurements of SST are already well established (Chelton and Wentz, 2005). A microwave satellite radiometer beyond the currently operational Global Precipitation Measurement – GPM Microwave Imager (Skofronick-Jackson et al., 2018) and Advanced Microwave Scanning Radiometer-2 (Kazumori et al., 2016) missions would provide the ability to maintain and further improve CDA at the air-sea interface. There is an immediate need to plan for a satellite salinity measurement mission beyond the 2020–2025 time frame (Durack et al., 2016; Vinogradova et al., 2017 this issue). Bearing in mind the collaborative nature of satellite missions, further coordination is needed for planning the next generation of NOAA satellites that follow the GOES-R, JPSS, DSCOVR, Jason-3, and COSMIC-2 missions (Volz et al., 2016).

Field campaigns and *in situ* measurements aid in the improvement of modeled near-surface temperature and salinity variations, and mixing processes. The existing network of drifting buoys [Figure 3 of Legler et al. (2015)] routinely reports near-surface (about 20 cm) measurements of SST, sea level pressure (SLP). The measured SLP is routinely assimilated into the NWP forecast models, and SST are used for calibration/validation of SST retrieval products. However, one cannot measure vertical SST variability and mixing with a single sensor (e.g., at 20 cm). Dedicated cruise campaigns such as those reported by Dong et al. (2017) suggest that adding one more temperature sensor and salinity sensor to the drifting buoy network can provide valuable measurements of SST/SSS near-surface variations. Such measurements would help with calibration and evaluation of observations as well as improve the representation of the diurnal cycle, the feedbacks between SST and surface salinity variations (Bellenger et al., 2017), and buoyancy-driven density variations in general.

OCEAN AND COUPLED EARTH SYSTEM REANALYSIS

An important application for DA is to develop historical reconstructions of the Earth system based on the observational record. Numerical models fulfill the basic large-scale equations of motion and satisfy conservation laws, but may have systematic errors. While this type of numerical modeling can provide insights into the mechanisms driving long-term variability (Haid et al., 2017), the systematic errors that arise can cause long-term drift in the modeled climate compared to the real Earth system. In contrast, statistical observational analyses (e.g., Abraham et al., 2013) can be applied to observed data to produce a full field reconstruction that closely agrees with the observational record. However, this approach does not typically ensure conservation laws are enforced, meaning there are known errors that are unaccounted for, and is not able to recover unobserved quantities. Retrospective analyses, or reanalyses, combine the advantages of both numerical modeling and statistical observation analyses to fulfill the conservation laws over discrete periods while also incorporating observed data and subsequently estimating unobserved quantities. Reanalyses can be used to study the evolution of the Earth's climate during any time period for which we have an observational record. They are also useful for initializing "reforecasts" that can be used to calibrate bias-correction schemes for seasonal forecasts. Next, we document recent advances from the ocean reanalysis community and discuss unresolved challenges that require sustained activities for maximizing the utility of information content from observations, supporting data rescue, and advancing specific research and development requirements for reanalyses.

ADVANCES AND UNSOLVED CHALLENGES IN PRODUCING OCEAN REANALYSES

The original interest in developing ocean reanalyses arose largely from a desire to examine long-range climate-scale signals. Ocean reanalyses can be studied to enhance understanding of processes driving observed changes. They are also useful for studying recent changes in the climate for quantities that are difficult to observe continuously, such as transports (Mignac et al., 2018), or those that require consistent spatial data coverage at depth, such as ocean heat content (Balmaseda et al., 2013; Wunsch and Heimbach, 2014). To be able to draw robust conclusions, one must be confident that inhomogeneous time series or abrupt regime changes are caused by physically consistent processes –

not artifacts associated with changes in the historical observing network. During much of the early history of ocean reanalysis development, there have been significant disagreements between estimates produced by different reanalysis approaches. This was due in large part to the scarcity of observational data, differences in model configurations, and discrepancies in DA methods.

However, due to advances in the ocean observing system, improvements in modeling, and advances in DA methods, ocean reanalysis products have been slowly converging.

To date, ocean reanalyses have been produced by many operational centers and research institutes (Carton and Giese, 2008; Sugiura et al., 2008; Xue et al., 2011; Chang et al., 2013; Wunsch and Heimbach, 2013; Blockley et al., 2014; Valdivieso et al., 2014; Köhl, 2015; Forget et al., 2015; Penny et al., 2015; Toyoda et al., 2016; Storto and Masina, 2016; Palmer et al., 2017; Zuo et al., 2017b). Balmaseda et al. (2015) provide a recent intercomparison study of about 20 reanalysis products. The extent to which reanalyses provide robust answers to questions about climate change and variability relies on many factors, including the fidelity of the numerical models, the accuracy of forcing fields, biases in observing platforms, uncertainties attributed to the observations and the background state (priors), and the sophistication of the DA schemes. Many of these considerations are highlighted in a recent study by Carton et al. (2019) comparing leading ocean reanalysis products (SODA3, ECCO4r3, and ORAS5).

Given the availability of ocean reanalysis products from multiple groups worldwide, we recommend that climate studies include the evaluation of as many products as possible to sample the range of uncertainty in the historical ocean state and disentangle possible inconsistencies that arise due to choices made in their construction. Uncertainties in ocean reanalysis state estimates result from accumulated errors from all system components (ocean model, boundary condition forcing, observations, and DA method). Uncertainty in ocean reanalyses as a whole can be studied using a multi-reanalysis ensemble approach (Balmaseda et al., 2015; Masina et al., 2017; Xue et al., 2017), which provides a way to not only investigate the accuracy of ocean reanalyses but also disentangle sources of uncertainty. A rough estimate can be achieved by comparing the consistency of the reanalyses (ensemble spread), interpreted as noise, with the natural variability (variance in time), interpreted as the signal.

Uncertainties in an individual system can also be assessed by accounting for errors explicitly in different system components, for example by using ensemble forecasts, by introducing stochastic perturbations in the model (Brankart et al., 2015), by estimating representativeness errors associated with observations in relation to the model resolution, and by estimating analysis/structure errors in forcing fields (Penny et al., 2015; Zuo et al., 2017a).

Surface forcing derived from atmospheric reanalyses induces systematic errors. Multi-forcing reanalyses may be performed to better estimate the impacts of these errors (Chaudhuri et al., 2013, 2016; Storto et al., 2016b; Carton et al., 2018; Yang et al., 2018). Recently, Zuo et al. (2017a) introduced a stochastic perturbation for the atmospheric forcing by taking into account both uncertainty from different atmospheric analysis data sets and uncertainty from the same analysis method with multiple ensemble members. Another method for adjusting uncertain atmospheric fields is by employing control methods, where adjustments to atmospheric surface forcing data are part of a formal inversion, assuming relatively accurate oceanic observations (e.g., Stammer et al., 2004; Liang and Yu, 2016). Uncertainty in initial conditions can also be evaluated using an ensemble approach, by performing several spin-up integrations with different DA system configurations (Zuo et al., 2018). Chevallier et al. (2017) showed that for coupled ocean-sea ice models driven by prescribed atmospheric forcing, part of the variability across ocean reanalyses is the result of differences in the atmospheric reanalyses used to force these systems, which is large in the polar regions (Lindsay et al., 2014). Part of the discrepancy in the atmospheric reanalyses is due to the treatment of the prescribed boundary conditions (e.g., sea ice), giving an example of a weaknesses in the "uncoupled" approach. Generally, both coupled climate models and ocean-ice models, driven by prescribed atmospheric forcing, cannot adequately represent the observed polar trends, whereas ocean reanalyses have proven quite adequate to capture these trends when observations are available to constrain the system (Chevallier et al., 2017; Uotila et al., 2018).

With the exception of smoother-based reanalyses generated by the Consortium for Estimating the Circulation and climate of the Ocean (ECCO; Wunsch and Heimbach, 2013; Köhl, 2015; Forget et al., 2015; Heimbach et al., 2019), most of the DA systems developed under GODAE and GODAE OceanView use some form of sequential DA (Martin et al., 2015). Some of the systems based on simplified assumptions about the forecast error characteristics suffer from problems with initialization, where the updates applied to the model at each assimilation step are not dynamically consistent. To date, many developers have attempted to minimize the negative impacts of these dynamical imbalances by *ad hoc* techniques such as nudging with incremental updates (Bloom et al., 1996). Some problems have been identified in the Equatorial region within a number of ocean reanalyses, in which the assimilation can induce spurious variability that has been damped by following several bias correction strategies (Waters et al., 2017).

An application of the 4D variational method in ocean DA has been developed with an emphasis on reconstructing the ocean on climate time scales (Stammer et al., 2016). Motivating these approaches were the goals of (i) using information contained in observations backward in time, (ii) enlarging the control space to include uncertain boundary conditions and model parameters, and (iii) deriving estimates with closed property budgets enforced by the equations of motion (e.g., Buckley et al., 2015; Piecuch et al., 2017). However, this approach also has potential limitations. For instance, increasing the control space also increases the dimension of the problem, which in turns makes the method very expensive for high-resolution global applications. There may also be challenges with relying on the accuracy of a linearization over long time windows.

Other difficulties are connected with the irregular observing network. This often causes spurious variability in reanalysis products, especially in multi-decadal reanalyses covering historical periods with highly varying observing systems ranging from the sparse pre-satellite era to present. This has been the subject of many investigations aiming to include bias-correction schemes within the reanalysis (Balmaseda et al., 2007; Lea et al., 2008; Storto et al., 2016a). However, this creates the additional challenge of estimating these biases while having only a limited number of "anchoring" (i.e., unbiased) observations. Before the deployment of the Argo network, the sampling of observations used by ocean reanalyses is generally sparse, which has implications for the reliability of quantities such as global ocean heat content before the 2000s. However, several studies showed that beginning in the early 1980s, the observing system is able to reasonably constrain the global ocean heat content (Storto et al., 2016b). There is growing interest amongst the ocean reanalysis community in the deep Argo program (Zilberman, 2017), with the hope that this will gradually fill the gap in knowledge of the ocean state below 2000 m and allow the deep ocean warming contribution to be assessed with greater precision. Care is also being taken in ocean reanalyses to synergistically exploit a large number of data sources (altimetry, gravimetry, Argo, tide-gauges, etc.) to create a reliable representation of freshwater and mass balances. Data used for evaluation, not necessarily assimilated (e.g., buoys, drifters, tide-gauges, RAPID and OSNAP arrays, SAMOC and SOCCOM programs, ADCP data, etc.) are also crucial for assessing uncertainty in reanalyses and improving process representation in models.

Within historical data records, the accuracy of the observations assimilated is often unknown or underestimated due to lack of metadata. This also prevents effective bias-correction procedures from being implemented and may lead to the erroneous specification of instrumental errors. For the historical ocean subsurface temperature record, the situation is improving through an internationally coordinated community effort (Domingues and Palmer, 2015)[1], focusing on recovery of data and metadata, development of intelligent metadata, coordinated quality control (automated and expert), and assignment of uncertainties. Their overall goal is to produce a long-term climate quality global ocean subsurface database that can be used with greater confidence by the ocean reanalysis community and other users. The first interim IQuOD database product is available from The IQuOD Team (2018).

Reanalyses will continue to extend further backward in time to cover longer historical periods, following the trend set by Compo et al. (2011) and ECMWF's ERA-20C, and later followed by comparable century-long ocean reanalyses (Giese et al., 2016; Yang et al., 2017) and the coupled reanalysis CERA-20C (Laloyaux et al., 2018a). This will require improved methods to handle sparse observations, discontinuities in the observation network, and correction of large-scale biases, as well as continuous efforts on data rescue. With the recent emergence of coupled Earth system reanalyses, non- oceanic data will also play an important role, particularly in time periods where ocean observations are extremely sparse or non-existent. Ocean background errors are expected to evolve significantly during the reanalysis period due to the ever-changing observing network. The development of time dependent background error covariance estimates has proved beneficial (Penny et al., 2015; Penny, 2017; Yang et al., 2017). The full introduction of flow-dependent background errors involves estimating the ocean background error covariances from the ensemble and developing methods to deal with sampling limitations. Such ensemble-based error covariance information can account for anisotropic and inhomogeneous correlations that are difficult to estimate with traditional methods. An Ensemble of Data Assimilation systems (EDA) showed some benefits in the atmosphere by dynamically changing the weight given to the background depending on the observation density (Poli et al., 2013) and such methods may be useful for the ocean as well.

In addition to climate investigations, ocean reanalyses using higher resolution eddy-permitting models have a long history among the members of the Global Ocean Data Assimilation Experiment (GODAE) and the follow-on GODAE OceanView. The production of high-resolution ocean reanalyses started naturally as a historical extension of operational analysis experiments, with a series of products disseminated by Mercator Ocean (Ferry et al., 2007, 2010; Garric et al., 2018), by CSIRO and the Bureau of Meteorology (Bluelink) (Oke et al., 2005, 2008, 2013), by NERSC (Sakov et al., 2012), and by JMA and JAMSTEC (Usui et al., 2017). These products have proved instructive for global and regional investigations of ocean variability (Schiller and Oke, 2015; Feng et al., 2016), ocean processes (Oke and Griffin, 2011), and for studies of the ocean-observing system (Lea et al., 2013; Fujii et al., 2015). Going forward, it is expected that the resolution of ocean reanalyses will increase to allow representation of eddy dynamics and to fully include mesoscale and coastal ocean dynamics. This requires the improvement of small-scale ocean dynamics in models and the development of DA methods that are capable of assimilating rapidly changing, strongly non-linear, and non-Gaussian observational constraints.

ADVANCES AND UNSOLVED CHALLENGES IN PRODUCING COUPLED REANALYSES

Coupled model integrations with prescribed radiative forcing have been the backbone of the coordinated experiments for the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project (CMIP) that were designed for contributing to the Intergovernmental Panel on Climate Change (IPCC). Century-long coupled reanalyses go a step further by assimilating information about the actual observed state of the Earth system, without deteriorating the model representation of low-frequency variability and change. While this is a tremendous challenge, it is essential in order to advance our understanding of climate variability and change and to identify the broader impacts on global communities.

Key benefits expected from a coupled reanalysis are: a more consistent treatment of the interfaces between different model components, better use of observations near these interfaces, and improved representation of global budgets of conserved quantities. In principle, the use of a coupled model as the

[1] www.iquod.org

forecast component within a DA system makes it possible to fully account for ocean-atmosphere, ocean- ice-atmosphere, and land-atmosphere feedbacks. This can only be achieved, however, if the assimilation of near-surface observations respects the consistency at the boundaries as imposed by the model and if the modeled dynamics at the boundary are consistent with observations.

In the 20th-century coupled reanalysis (CERA-20C) produced at ECMWF, the ocean and the atmosphere communicate hourly through air-sea coupling at the outer-loop level of the variational method. In this system, changes in the state of the atmosphere indirectly impact the ocean properties, and vice-versa, and both systems adjust to each other during each analysis cycle. There is a more consistent energy balance in CERA-20C, with the net heat fluxes at the air-sea interface (0.15 ± 1.1 W/m^2) and ocean temperature increments (-0.11 ± 1.9 W/m^2) averaging close to zero over the century, compared to the forced ocean reanalysis ORA-20C (-1.62 ± 1.89 W/m^2 and 1.66 ± 2.32 W/m^2). However, given that the SST in the ocean component of CERA-20C was nudged toward an external data product, this suggests that there is further room for improvement. While midlatitude storms, heat waves, or cold-air outbreaks are often well-represented in regions with dense observational coverage, this is not always the case for tropical cyclones, which are difficult to model and not well-constrained by observations. CERA-20C struggles to correctly represent several tropical cyclones at the beginning of the 20th century (Laloyaux et al., 2018a). More work is needed to quality control observations from the International Best Track Archive for Climate Stewardship (IBTrACS). This is expected to improve the ability of historical reanalyses to facilitate the study of weather extremes. Based on the development of CERA at ECMWF, which implements the Copernicus Climate Change Service[2] on behalf of the European Union, there are ambitions to produce a moderate-resolution global coupled centennial reanalysis by 2022, allowing a better representation of long-term trends in the climate system.

Beyond CERA-20C, ECMWF's reanalysis portfolio has recently been extended to include CERA-SAT (Schepers et al., 2018), a pilot reanalysis for coupled DA using the full modern atmospheric and ocean-observing systems. CERA-SAT was produced using ECMWF's CERA coupled assimilation system and constitutes a 10-member EDA available for a 9-year period from January 1, 2008 to December 31, 2016. CERA-SAT serves as a proof-of-concept for CDA in the context of modern NWP-observing systems. Preliminary assessments have shown ocean-atmosphere coupling to be beneficial in tropical regions, while degradation is evident in the extra tropics, when comparing the coupled CERA-SAT system using SST nudged to OSTIA to an atmosphere-only reanalysis of the same setup but forced with OSTIA SST.

Centers that routinely produce reanalyses are often also engaged in other activities (for instance, operational prediction, mission support, and ocean monitoring). In order to carry out all of these missions, and to successfully transition the currently in-production uncoupled reanalyses to future coupled reanalyses requires careful planning for appropriate computational and storage resources. We highly recommend that funding agencies plan for such upcoming future needs in order to dedicate sufficient resources to support, within the next decade, not only coupled ocean-atmosphere reanalyses but also the inclusion of additional components, such as atmospheric constituents, chemistry, and ocean biogeochemistry. Such efforts are underway in the United States as detailed in NOAA's strategic implementation plan (SIPv4, 2017), which is a partnership among NASA, NOAA, the Department of Defense (DoD), and the Joint Center for Satellite Data Assimilation (JCSDA) and contributing external and international agencies.

[2]climate.copernicus.eu

USING OCEAN OBSERVATIONS TO IMPROVE PREDICTION

We next describe the existing observing system and gaps in observational coverage and recommend designs of observational and modeling experiments to evaluate the impact of ocean observations on forecast skill. The advances and enhanced spatial and temporal resolution obtained over the last 10 years in both satellite and *in situ* observations have enabled the use of DA to constrain coupled Earth system models for the first time to a realistic representation of the large-scale upper ocean thermal structure (upper 1000 m). However, there are still components of the coupled system that remain unconstrained. For example, the lack of air-sea flux measurements with global coverage poses a challenge to constraining the atmosphere-ocean exchanges without adequate observational sampling. This type of observing network should be enhanced in the future as they are not only crucial in the context of CDA and its applications to S2S and decadal prediction but also for the evaluation of climate simulations. In particular, we recommend the development of air-sea-flux-observing satellite missions.

We emphasize the need for continuous long observational records to enhance prediction capabilities. Ocean reanalysis systems naturally extend to the initialization of seasonal, interannual, and decadal prediction systems, where the role of subsurface ocean initialization has been recognized as crucial (Balmaseda et al., 2009). S2S and decadal forecasting typically rely on the existence of reforecasts covering several decades in order to calibrate the model output and for skill assessment. These reforecasts are initialized by ocean or coupled reanalyses (Balmaseda, 2017). The length of the reforecast record adds value to the forecast. For this purpose, sustained data rescue activities are recommended as well as maintaining stability of the existing observing system. Recently, ocean reanalyses used to initialize seasonal prediction systems (reforecasts and near real-time reanalyses) have become publicly available via the EU-funded Copernicus Programme and are being used to evaluate subsequent forecasts (Juricke et al., 2018).

Measurements from observing platforms such as satellites, moored surface and subsurface buoys, drifters, floats, dedicated manned and unmanned vehicles, research ships, and vessels of opportunity are collected and distributed with various time lags. Operational predictions rely on observational platforms equipped with the capability for distribution in real-time or near real-time. Some observation types are used primarily as independent measurements for evaluation because they cannot be assimilated due to time delays or other technical complications. These include ocean current profilers, satellite-derived ocean surface currents, and a suite of biogeochemical observations such as carbon, oxygen, nutrients, ocean color, and phytoplankton.

Overall, a lack of uniformity in data management infrastructures imposes problems for the effective and efficient use of the global observing system in prediction efforts. These issues include, but are not limited to, delayed and duplicate data receipts, versioning issues, missing data and metadata, and non-documented data processing procedures. In order to advance the deployment of effective ocean-observing systems, modern data management infrastructures are needed such that all activities along the data flow pipeline, from data collection through assembly and preservation, are more automated and fault-tolerant and progressively advance the systems toward interoperability. Building strong collaboration amongst the observing networks, data managers, and decadal forecasting centers will lead to improved access and uptake of data and to efficiencies that will eventually lead to improvements both in the observing networks and the decadal prediction system.

The future ocean observational requirements for the decadal prediction system include sustained and reliable data streams that have global sampling and are continuous in time, subject to regular quality control and calibration procedures, and encompass several spatial and temporal scales (e.g., National Academies of Sciences, Engineering, and Medicine [NASEM], 2017). To this end, there is great value to centralized data centers that collate observations from individual observing platforms in order to provide timely access to data and a consistent data format for ease of integration into DA systems.

PREDICTION AT SUBSEASONAL TO SEASONAL TIMESCALES

Many operational prediction centers are currently undertaking a transition from atmospheric NWP on a time range of 0–2 weeks to seamless forecasts that bridge the gap between medium-range weather and seasonal forecasts. This transition is driven by a growing consensus that coupled Earth system modeling benefits forecasts on a wide range of timescales (Hoskins, 2013; Vitart et al., 2017). The new focus on prediction with coupled models is highlighted in efforts such as forecasting the onset of monsoons, characterizing teleconnections of the MJO, and providing advance warning for extreme weather events (Vitart and Robertson, 2018).

Subseasonal prediction, focusing on the period transitioning from NWP to seasonal timescales, stands to gain considerably from combining the higher model resolutions of NWP with the coupled modeling approach of seasonal prediction. The MJO is the dominant mode of intraseasonal variability in the tropics and is considered a major source of predictability on the subseasonal time scale (Waliser, 2011). With respect to the ocean, anomalies in SST affect air-sea heat fluxes and affect atmospheric circulation (Woolnough et al., 2007).

Vitart et al. (2014) indicated significant gains in prediction skill after a decade of producing operational forecasts at ECMWF, pointing to an average gain of about 1 day of MJO prediction skill per year and improved ability to predict the North Atlantic Oscillation (NAO) and sudden stratospheric warmings (SSW). Skill scores improve with increased horizontal resolution and the addition of new modeling components such as a dynamic sea ice model. The introduction of new modeling components also presents the opportunity to assimilate new observational data not previously utilized for sub-seasonal prediction. Zampieri et al. (2018) indicate high potential for sea ice prediction in the sub-seasonal timescales, especially for late summer forecasts, and advocate the need to reduce systematic seasonally dependent model biases and develop advanced DA capabilities to constrain sea ice extent and sea ice thickness.

Zhu et al. (2018) showed that MJO forecast skill can be improved in the NCEP Global Ensemble Forecast System (GEFS) from an average of 12.5 days (control) to nearly 22 days by (1) adding stochastic physical perturbations, (2) considering ocean impacts by using a two-tiered sea surface temperature approach (combing an analysis product with a forecast of SST from a coupled model), and (3) applying a new scale-aware convection scheme to improve the model physics for tropical convection. They also showed improved ensemble mean anomaly correlation of 500-hPa geopotential height in the extratropics over weeks 3 and 4.

El-Niño Southern Oscillation is an inherently coupled phenomenon and one of the most studied sources of interannual variability in the climate system (Wu et al., 2009). Though mostly associated with the tropical Pacific, ENSO variability impacts the global climate (Timmermann et al., 2018). Changes in SST are an indicator of changes in ocean heat storage and transport and these oceanic processes further interact with changing atmospheric momentum and heat fluxes. Prediction skill for the SSTs associated with ENSO have improved over time. At ECMWF, for example, the skill in predicting SST anomalies in the NINO3.4 region has consistently improved as the DA system evolved starting from the S1 system in 1997. If subsurface ocean and satellite altimeter observations are withheld from the analysis, there is a severe degradation in skill comparable to 15 years of progress in seasonal forecasting (**Figure 1**).

The original motivation for the Tropical Atmosphere-Ocean (TAO) array and Triangle Trans-Ocean Buoy Network (TRITON) was the 1982–1983 ENSO event (McPhaden, 1995; Ando and Kuroda, 2002). These moorings have provided surface meteorological observations, ocean temperatures in the upper 500 m, salinity and current measurements at selected moorings, and have played a key role in better understanding the ENSO phenomenon and advancing seasonal forecast systems in the decades since their implementation (McPhaden et al., 2010). To support S2S prediction, new observing systems must account for processes occurring over a much broader range of timescales.

Innovative observing technology in the sub-surface layer and at the air-sea interface can help to improve understanding of coupled interactions critical for S2S prediction. Self-sailing

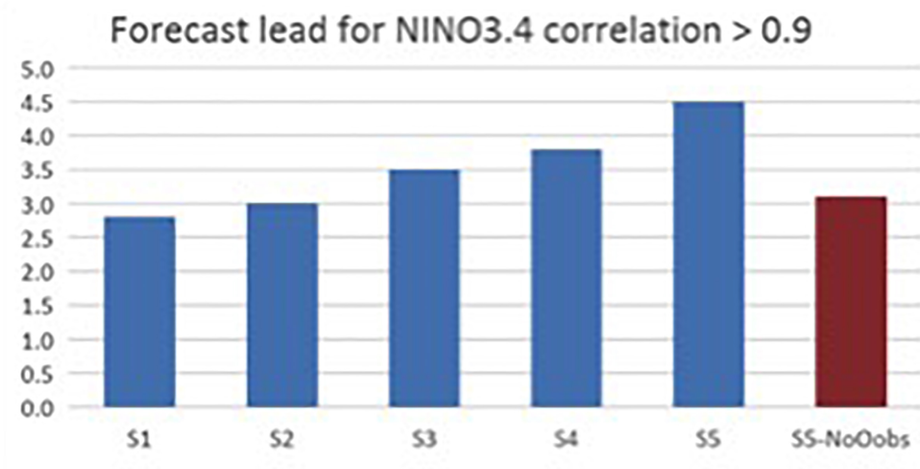

FIGURE 1 | Lead time in months at which NINO3.4 SST anomaly correlation drops below 0.9 over the period 1987–2002. Results are given for five generations of seasonal forecasting systems at ECMWF (S1–S5). A version of SEAS5 without ocean data assimilation (SEAS5-NoOobs) is given for reference from Stockdale et al. (2018).

boats currently exist that can autonomously gather ocean and atmospheric observations over large areas of the ocean surface. Such technologies have the potential to precipitously drop costs of collecting observations of quantities such as wind, temperature, humidity, salinity, dissolved oxygen, and fluorescence near the ocean surface. These technologies are promising for constraining surface flux estimates in CDA, leading to improved modeling of air-sea interaction and improved initialization of coupled model forecasts. S2S forecasts for high latitudes and midlatitudes can be improved with more numerous and accurate ocean and sea-ice observations in data-sparse regions.

A redesign of the TAO/TRITON array is currently underway by the Tropical Pacific Observing System (TPOS-2020) working group[3] that is largely influenced by the volume of new complementary data provided by a number of new observing platforms. TPOS-2020 currently plans a "backbone" design that will support and supplement the broader observing network, including satellite measurements. The TPOS-2020 design is likely to include measurements of the air-sea interface with a vertical and temporal resolution not possible from remote-sensing platforms. Complementary observations include satellite measurements of quantities such as sea level, SST, SSS, wind stress, and precipitation (Mason et al., 2010; National Academies of Sciences, Engineering,, and Medicine [NASEM], 2018, Chp. 2) as well as the *in situ* Argo profiling float program (see Legler et al., 2015 for a comprehensive review of operational observing systems).

The tropical Atlantic and Indian Oceans are also locations of strong air-sea interaction, exhibiting their own local dominant modes of interannual variability, such as the Indian Ocean Dipole (Saji et al., 1999; Webster et al., 1999) and the Atlantic Niño (Wang, 2005), both of which can modify the timing and expression of ENSO. To track the evolving state of these oceans the TAO mooring design has gradually been extended to the Prediction and Research Moored Array in the Tropical Atlantic (PIRATA) and more recently the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) in the tropical Indian Ocean.

The requirements of an observing system change in the Arctic, where the Argo float network is limited due to seasonal ice cover and strong stratification and where satellite remote sensing is limited by heavy cloud cover. These environmental challenges, along with increasing recognition of the importance of seasonal changes in Arctic and their impact on weather systems, has led to rapid development of new instrument types. As regular data from these new instruments become available, evaluation of their impact on S2S forecasts will be needed.

Prediction centers have been slow to incorporate SSS data in ocean DA systems (Maes et al., 2014), though there have been some indications of potential benefits for upper ocean processes that could impact S2S and decadal prediction. Hackert et al. (2011, 2014), Zhu et al. (2014), Tranchant et al. (2018), and Martin et al. (2019) indicated that improved salinity estimates have the potential to improve ENSO forecasts. Though, to date, the impacts shown have been somewhat minor. A number of other studies showed positive impacts due to the assimilation of SSS in controlled experiments, including improved upper ocean salinity (Vernieres et al., 2014), improved surface currents, mixed-layer depth, and barrier layer thickness (Chakraborty et al. (2014, 2015), and improved temporal variability of the vertical distribution of salinity in areas with large freshwater input (Seelanki et al., 2018). Still, the low temporal frequency of the data, large uncertainty estimates attributed to instantaneous observations, and large platform-specific biases (Bao et al., 2019), make the assimilation of SSS a continuing challenge. A next-generation technology that could produce SSS observations with

[3]http://tpos2020.org/

the frequency, accuracy, and coverage of SST observations would be a high-impact capability.

Observing system experiments conducted with real-time forecasting systems have found utility in assimilating sea level observations from multiple altimeters (Lea et al., 2014; Oke et al., 2015a,b). For example, Lea et al. (2014) showed that withholding Jason-2 data resulted in a 4% increase in the global RMS SSH innovations, while withholding all altimeter data resulted in a 16% increase of the global RMS SSH innovations. Verrier et al. (2017) conducted observing system simulation experiments with an eddy-permitting model (1/4-degree horizontal resolution) and found that forecasts of sea level and ocean currents are continually improved when incrementally increasing the number of satellite altimeters from one to two (∼30% error reduction) and from two to three (∼10% additional error reduction). They also note that when assimilating several altimeters, the analysis can resolve western boundary current scales closer to 100 km, versus the native model's capability to resolve scales around 100–200 km.

Further evaluating observing system impacts on ocean analyses and S2S forecasts will contribute to an ongoing discussion in the design of new oceanic observing systems, such as TPOS-2020 and AtlantOS[4]. Additionally, new and upcoming satellite missions such as the Surface Water and Ocean Topography (SWOT) will provide higher-fidelity SSH observations than ever before. Coordination between international groups such as CLIVAR and GODAE OceanView is needed for significant progress to be made with international observing efforts (Fuiji, 2019). These international efforts, together with Global Ocean Observing System (GOOS) and its expert panels focusing on physics and biogeochemistry need to work together to build an observing system that recognizes user priorities.

PREDICTION AT DECADAL CLIMATE TIMESCALES

Interest in the viability of decadal forecasts is driven by a recognition that these timescales are of increasing importance to decision makers both for governmental policy and private industry (Meehl et al., 2009; Kirtman et al., 2013). Decadal prediction can encompass timescales between several years to a few tens of years, with relevant processes interwoven with those relevant to both S2S forecasts and long- term climate projections. In the extratropics, for example, distinct climate variability has been associated with annual changes in the storm tracks and associated meteorological conditions over the North Pacific and North Atlantic, such as the Pacific Decadal Oscillation (PDO) and the North Atlantic Oscillation (NAO) (Scaife et al., 2014). Decadal prediction is dependent on our ability to forecast not only internal variability of the Earth's climate system, such as the large-scale climate modes (ENSO, NAO, and PDO), but also how these modes will change under the influence of changes in external forcing, such as arising from human activity. The World Climate Research Program (WCRP) has recognized near-term climate prediction as one of its grand challenges. Despite this recognition, the extent to which decadal climate predictions are able to provide reliable and useful information to users remains uncertain (Meehl et al., 2014).

A sufficiently well observed ocean is crucial for the development of useful decadal predictions (Smith et al., 2012). In order to predict the evolution of natural climate variability, coupled models must be initialized with observations informing the current state of the climate system.

Predictability over these timescales will rely principally on accurately forecasting the slower modes of the coupled climate system, which are highly dependent on long-timescale ocean dynamics. Thus, decadal prediction systems will rely ever more heavily on a sustained ocean-observing system to initialize and verify predictions, similarly to what happened for NWP systems. Sparseness, non-uniformity, and secular changes in the ocean observing system represent a challenge for the initialization and evaluation of a decadal prediction system. Therefore, key factors enabling improved climate prediction skill are the availability of consistent surface and subsurface ocean observations over sufficiently long time spans, improved understanding of processes involved with ocean-atmosphere coupling, and the ability to track the climate modes of variability that determine predictability on a given spatiotemporal scale.

During the last decade, satellites and autonomous *in situ* platforms have driven a step change in our ability to observe the ocean in near real-time. The use of remotely sensed and autonomous *in situ* platforms has revolutionized the ocean observing system, and the fast, technological advance on platforms and sensors will continue to improve the system (**Figure 2**). The next decade will expand upon these advances with new sensors and platforms, coupled with advances in telecommunications.

Decadal prediction systems generally assimilate or relax to SST analysis products. However, an increasing number of systems are also including interior ocean observations, such as temperature and salinity profiles, and sea ice (Doblas-Reyes et al., 2011; O'Kane et al., 2018). Decadal prediction systems, as they focus on seasonal to longer timescales, rely on both real-time data and delayed-mode quality assurance and quality control data (QA/QC) for model initialization and evaluation. Coupled decadal prediction systems often use atmospheric states sampled either from reanalyses or operational products to initialize the atmosphere. However, this practice may need to be revisited and potentially replaced with more sophisticated methods such as CDA. For example, comparison of these products with the sparsely available ocean surface meteorological flux buoys consistently show significant differences both globally and regionally, indicating imbalances in the surface energy and freshwater fluxes at the air- sea interface (Yu, 2019). Maintaining and extending surface flux buoys is vital to understanding the source of these inconsistencies, to improving coupled models, and to evaluating decadal prediction systems.

The heterogeneous nature of the *in situ* ocean-observing system requires comprehensive metadata, sophisticated data integration, and organized interpretation activity in order to

[4]https://www.atlantos-h2020.eu

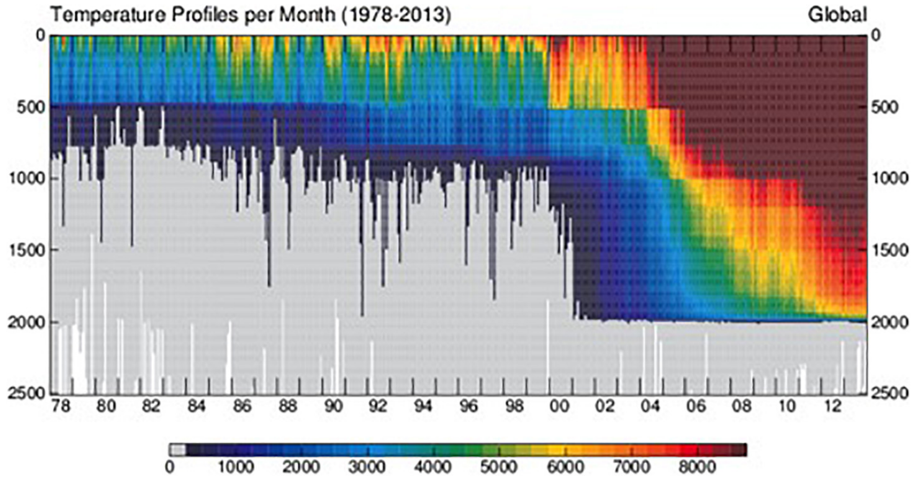

FIGURE 2 | Global availability of *in situ* temperature profiles by vertical depth from 1978 to 2013.

realize the maximum benefit of the observations. Effective data management requires a strong collaborative effort across activities including observation collection, metadata and data assembly using community accepted standards, QA/QC, data publication that enables local and interoperable access, and secure archiving that guarantees long-term preservation of collected data.

Statistics of the innovations generated within the DA procedure can be evaluated to identify broad biases in the differences between model and observations. For example, one can identify regions where there are large innovations due to the assimilation of daily, satellite SSH and SST anomalies.

Significant impacts are often found in the dynamically active regions such as the high-latitude oceans, boundary currents, and along the Equator. Further, with appropriate DA methods, regions of large model biases can be accurately estimated and reduced via direct assimilation of observations (Evensen, 2003). On longer timescales, the sparser *in situ* observing network can provide similar guidance for correcting long-timescale model biases.

There remain many unanswered questions on the fundamental nature and drivers of ocean variability. Decadal prediction depends on the presence of "oscillations" that have the potential to remain coherent on multi-year to multi-decadal time scales. To the extent that such slowly evolving dynamical regimes exist (e.g., along which climate anomalies propagate), it is important that the DA system is capable of maintaining these lower frequency signals. It is also critical to understand how these anomalous ocean signals are influenced by the ocean-atmosphere boundary. Improved dynamical understanding of the ocean, sea ice, and atmosphere, and their coupled interfaces and teleconnections, will lead to more reliable and skillful multi-year to decadal climate forecasts.

There is a need for full-depth observations that provide measurements able to resolve the dominant temporal and spatial scales of variability of the ocean. We encourage continuing to leverage the sustained ocean-observing infrastructure for short-term intensive process study campaigns that target key knowledge gaps such as air-sea-land and ice coupling. When such process studies are conducted, greater interaction with the DA community before, during, and after the campaigns could help to identify observations that may be good candidates for transitioning into the sustained observing system. To this end, we encourage stronger collaboration between the communities developing near-term forecasting and ocean observing platforms to aid model development and observational design.

CONCLUSION

The ocean-observing system plays an important role in developing historical reconstructions of the ocean and initializing forecasts of the coupled Earth system at all timescales. The ideal observational sampling strategy will continue to evolve as we improve our understanding of the spatial and temporal scales of ocean variability and as technological observing capabilities improve. An ongoing challenge for the reanalysis and prediction communities will be to maintain close collaboration with the ocean-observing community that is developing the next-generation ocean-observing systems. This collaboration should occur at all stages, including the design, implementation, and decision making that determines sustained observations. The ocean DA community should provide programmatic guidance to the ocean-observing community regarding what types of observations would be most useful when established in a sustained observing network to best support ocean monitoring and prediction at various timescales. This problem requires the solution of a complicated optimization problem that is defined by a stated goal (e.g., to maximize the skill of a forecast), while taking into account the limitations of the forecast model, of each observing platform, and of the DA method itself. So far, this is not a mainstream activity and further coordination is needed in the coming decade to make observing system design a key application of ocean DA and CDA.

We anticipate a continuing race between the physical scales resolved by modeling and observing systems. DA systems must be able to constrain increasingly high-resolution numerical models at physical scales supported by the observation network. This poses dual challenges to make better use of a sparse observing system that will become increasingly coarse, in a relative sense, as model resolutions increase, as well as the need to incorporate as much information as possible from high-resolution satellite observing systems. With upcoming satellite missions, the satellite-based ocean-observing system may at times evolve to support much higher resolutions of observed data products than a state-of-the-art operational forecast model can support. While a precise DA strategy should be developed for such scenarios, we also encourage coordination to take place between the modeling and prediction centers and the teams developing plans for future satellite observing missions in order to ensure prioritization of those missions that have maximum impact on prediction skill.

To support CDA developments for operational applications, we recommend that a high priority be placed on ensuring consistency between atmosphere and ocean data governance bodies (e.g., WMO and Copernicus Climate Change Service and Copernicus Marine Environment Monitoring Service). At present, many ocean observations risk missing the cut-off times associated with the timelines of operational NWP. Improved infrastructure is needed to support research and operations, including real-time transmission of observed data and real-time feedback from users regarding the quality control of those data relative to other observing sources. For operational coupled Earth system approaches, used for reanalyses and prediction, it is crucial to enhance the consistency between the atmospheric and the ocean-observing systems, not only in terms of timeliness and infrastructure but also in terms of funding support and sustainability. The European Environment Agency State of Play Report (The European Environment Agency [EEA], 2017) pointed out that the ocean-observing system lacks prospects for long term funding. About 70% of data in the GOOS is funded by time-limited research projects (in contrast to 25% for atmospheric observations). *In situ* ocean observations are based on infrastructures mainly supported by national agencies, and in recent years the number of observation sites and platforms have gone through periods of decline. They also emphasized that more coordination is needed between funding agencies, operators, and users of ocean observations internationally. In addition, the EEA State of Play report emphasized the lack of biogeochemical and deep (2000 m and deeper) ocean observations.

Finally, the combination of increases in computing power and availability of observations has enabled the development of ensemble coupled DA systems. Ensemble-based approaches have the ability to identify and track the largest growing disturbances within the system. These growing disturbances represent regions of high variance where potential predictability of the system resides. The identification of these growing disturbances provides information about regions of the ocean where observations are likely to have the largest impact on the evolving coupled system and likely lead to useful predictions at all scales. Emerging CDA methods, enabled by coupled Earth system modeling, provide a great opportunity for increased collaboration across communities and rapid advances in scientific understanding over the next decade.

AUTHOR CONTRIBUTIONS

All authors contributed to a group writing of this review manuscript. SP was the lead coordinator and writer. AM and MM (ocean data assimilation), SP (coupled data assimilation), SA (CDA of radiance data for SST), AS (ocean reanalysis), AS (S2S prediction), and BS (decadal prediction) were section leads for each subsection of the manuscript.

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REFERENCES

Abraham, J. P., Baringer, M., Bindoff, N. L., Boyer, T., Cheng, L. J., Church, J. A., et al. (2013). A review of global ocean temperature observations: implications for ocean heat content estimates and climate change. *Rev. Geophys.* 51, 450–483. doi: 10.1002/rog.20022

Akella, S., Todling, R., and Suarez, M. (2017). Assimilation for skin SST in the NASA GEOS atmospheric data assimilation system. *Q. J. R. Meteorol. Soc.* 143, 1032–1046. doi: 10.1002/qj.2988

Anderson, C. R., Kudela, R. M., Kahru, M., Chao, Y., Rosenfeld, L. K., Bahr, F. L., et al. (2016). Initial skill assessment of the California harmful algae risk mapping (C- HARM) system. *Harmful Algae* 59, 1–18. doi: 10.1016/j.hal.2016.08.006

Ando, K., and Kuroda, Y. (2002). Two modes of salinity and temperature variation in the surface layer of the pacific warm pool. *J. Oceanogr.* 58, 599–609.

Balmaseda, M. A. (2017). Data assimilation for Initialization of seasonal forecasts. The sea: the science of ocean prediction. *J. Mar. Res.* 75, 331–359. doi: 10.1371/journal.pcbi.1004239

Balmaseda, M. A., Alves, O., Arribas, A., Awaji, T., Behringer, D., Ferry, N., et al. (2009). Ocean initialization for seasonal forecasts. *Oceanography* 22, 154–159. doi: 10.5670/oceanog.2009.73

Balmaseda, M. A., de Rosnay, P., Hersbach, H., Keeley, S., McNally, T., and Tietsche, S. (2018). *Workshop on Observations and Analysis of Sea-Surface Temperature and Sea Ice for NWP and Climate Applications*. Reading: ECMWF.

Balmaseda, M. A., Dee, D., Vidard, A., and Anderson, D. L. (2007). A multivariate treatment of bias for sequential data assimilation: application to the tropical oceans. *Q. J. R. Meteorol. Soc.* 133, 167–179. doi: 10.1002/qj.12

Balmaseda, M. A., Hernandez, F., Storto, A., Palmer, M. D., Alves, O., Shi, L., et al. (2015). The ocean reanalyses intercomparison project (ORA-IP). *J. Operat. Oceanogr.* 8, s80–s97. doi: 10.1080/1755876X.2015.1022329

Balmaseda, M. A., Trenberth, K. E., and Källén, E. (2013). Distinctive climate signals in reanalysis of global ocean heat content. *Geophys. Res. Lett.* 40, 1754–1759. doi: 10.1002/grl.50382

Bao, S., Wang, H., Zhang, R., Yan, H., and Chen, J. (2019). Comparison of satellite-derived sea surface salinity products from SMOS, Aquarius, and SMAP. *J. Geophys. Res.* 124, 1932–1944. doi: 10.1029/2019JC014937

Becker, E. A., Forney, K. A., Fiedler, P. C., Barlow, J., Chivers, S. J., Edwards, C. A., et al. (2016). Moving towards dynamic ocean management: how well do modeled ocean products predict species distributions? *Remote Sens.* 8:149. doi: 10.3390/rs8020149

Bell, M. J., Schiller, A., Le Traon, P. Y., Smith, N. R., Dombrowsky, E., and Wilmer-Becker, K. (2015). An introduction to GODAE oceanview. *J. Operat. Oceanogr.* 8, s2–s11. doi: 10.1080/1755876X.2015.1022041

Bellenger, H., Drushka, K., Asher, W., and Reverdin, G. (2017). Extension of the prognostic model of sea surface temperature to rain-induced cool and fresh lenses. *J. Geophys. Res.* 122, 484–507. doi: 10.1002/2016jc012429

Bertino, L., and Holland, M. M. (2017). Coupled ice-ocean modeling and predictions. *J. Mar. Res.* 75, 839–875. doi: 10.1357/002224017823524017

Blockley, E. W., Martin, M. J., McLaren, A. J., Ryan, A. G., Waters, J., Lea, D. J., et al. (2014). Recent development of the Met Office operational ocean forecasting system: an overview and assessment of the new Global FOAM forecasts. *Geosci. Model. Dev.* 7, 2613–2638. doi: 10.5194/gmd-7-2613-2014

Bloom, S. C., Takacs, L. L., da Silva, A. M., and Ledvina, D. (1996). Data assimilation using incremental analysis updates. *Mon. Wea. Rev.* 124, 1256–1271. doi: 10.1175/1520-0493(1996)124<1256:dauiau>2.0.co;2

Bolton, T., and Zanna, L. (2019). Applications of deep learning to ocean data inference and subgrid parameterization. *JAMES* 11, 376–399. doi: 10.1029/2018ms001472

Brankart, J.-M., Candille, G., Garnier, F., Calone, C., Melet, A., Bouttier, P.-A., et al. (2015). A generic approach to explicit simulation of uncertainty in the NEMO ocean model. *Geosci. Model Dev.* 8, 1285–1297. doi: 10.5194/gmd-8-1285-2015

Brasseur, P., Gruber, N., Barciela, R., Brander, K., Hobday, A. J., Huret, M., et al. (2009). Integrating biogeochemistry and ecology into ocean data assimilation systems. *Oceanography* 22, 206–215. doi: 10.5670/oceanog.2009.80

Brassington, G. B., Martin, M. J., Tolman, H. L., Akella, S., Balmeseda, M., Chambers, C. R. S., et al. (2015). Progress and challenges in short- to medium-range coupled prediction. *J. Operat. Oceanogr.* 8, s239–s258. doi: 10.1080/1755876X.2015.1049875

Brunke, M. A., Zeng, X., Misra, V., and Beljaars, A. (2008). Integration of a prognostic sea surface skin temperature scheme into weather and climate models. *J. Geophys. Res.* 113:D21117.

Buckley, M. W., Ponte, R. M., Forget, G., and Heimbach, P. (2015). Determining the origins of advective heat transport convergence variability in the North Atlantic. *J. Clim.* 28, 3943–3956. doi: 10.1175/JCLI-D-14-00579.1

Carton, J. A., Chepurin, G. A., Chen, L., and Grodsky, S. A. (2018). Improved global net surface heat flux. *J. Geophys. Res.* 123, 3144–3163. doi: 10.1002/2017JC013137

Carton, J. A., and Giese, B. S. (2008). A reanalysis of ocean climate using simple ocean data assimilation (SODA). *Mon. Weather Rev.* 136, 2999–3017. doi: 10.1175/2007mwr1978.1

Carton, J. A., Penny, S. G., and Kalnay, E. (2019). Temperature and Salinity Variability in the SODA3, ECCO4r3, and ORAS5 Ocean Reanalyses, 1993–2015. *J. Clim.* 32, 2277–2293. doi: 10.1175/JCLI-D-18-0605.1

Casey, K. S., Brandon, T. B., Cornillon, P., and Evans, R. (2010). in *The Past, Present and Future of the AVHRR Pathfinder SST Program. Oceanography from Space*, eds V. Barale, J. F. R. Gower, and L. Alberotanza (Berlin: Springer). doi: 10.1175/jcli-d-18-0605.1

Castro, S. L., Wick, G. A., and Emery, W. J. (2012). Evaluation of the relative performance of sea surface temperature measurements from different types of drifting and moored buoys using satellite7 derived reference products. *J. Geophys. Res.* 117:C02029. doi: 10.1029/2011JC007472

Chakraborty, A., Sharma, R., Kumar, R., and Ba, S. (2014). A SEEK filter assimilation of sea surface salinity from Aquarius in an OGCM: implication for surface dynamics and thermohaline structure. *J. Geophys. Res.* 119, 4777–4796. doi: 10.1002/2014JC009984

Chakraborty, A., Sharma, R., Kumar, R., and Basu, S. (2015). Joint assimilation of Aquarius-derived sea surface salinity and AVHRR-derived sea surface temperature in an ocean general circulation model using SEEK filter: implication for mixed layer depth and barrier layer thickness. *J. Geophys. Res.* 120, 6927–6942. doi: 10.1002/2015JC010934

Chang, Y.-S., Zhang, S., Rosati, A., Delworth, T. L., and Stern, W. F. (2013). An assessment of oceanic variability for 1960–2010 from the GFDL ensemble coupled data assimilation. *Clim. Dyn.* 40, 775–803. doi: 10.1007/s00382-012-1412-2

Chaudhuri, A. H., Ponte, R. M., and Forget, G. (2016). Impact of uncertainties in atmospheric boundary conditions on ocean model solutions. *Ocean Model.* 100, 96–108. doi: 10.1016/j.ocemod.2016.02.003

Chaudhuri, A. H., Ponte, R. M., Forget, G., and Heimbach, P. (2013). A comparison of atmospheric reanalysis surface products over the ocean and implications for uncertainties in air–sea boundary forcing. *J. Clim.* 26, 153–170. doi: 10.1175/JCLI-D-12-00090.1

Chelton, D. B., and Wentz, F. J. (2005). Global microwave satellite observations of sea surface temperature for numerical weather prediction and climate research. *Bull. Am. Meteorol. Soc.* 86, 1097–1116. doi: 10.1175/bams-86-8-1097

Chelton, D. B., and Xie, S.-P. (2010). Coupled ocean-atmosphere interaction at oceanic mesoscales. *Oceanography* 23, 52–69. doi: 10.5670/oceanog.2010.05

Chevallier, M., Smith, G. C., Dupont, F., Lemieux, J.-F., Forget, G., Fujii, Y., et al. (2017). Intercomparison of the Arctic sea ice cover in global ocean-sea ice reanalyses from the ORA-IP project. *Clim. Dyn.* 49, 1107–1136. doi: 10.1007/s00382-016-2985-y

Ciavatta, S., Kay, S., Saux-Picart, S., Butenschön, M., and Allen, J. I. (2016). Decadal reanalysis of biogeochemical indicators and fluxes in the North West European shelf-sea ecosystem. *J. Geophys. Res. Oceans* 121, 1824–1845. doi: 10.1002/2015jc011496

Compo, G. P., Whitaker, J. S., Sardeshmukh, P. D., Matsui, N., Allan, R. J., Yin, X., et al. (2011). The twentieth century reanalysis project. *Quart. J. Roy. Meteor. Soc.* 137, 1–28. doi: 10.1002/qj.776

Dee, D. P., Balmaseda, M., Balsamo, G., Engelen, R., Simmons, A. J., and Thépaut, J.-N. (2014). Toward a consistent reanalysis of the climate system. *Bull. Am. Meteorol. Soc.* 95, 1235–1248. doi: 10.1175/bams-d-13-00043.1

Derber, J., and Li, X. (2018). *Assimilating SST With an Atmospheric DA System*. Available at: https://www.ecmwf.int/sites/default/files/elibrary/2018/17984-assimilating-sst-atmospheric-da-system.pdf (accessed January 2018).

Doblas-Reyes, F. J., Balmaseda, M. A., Weisheimer, A., and Palmer, T. N. (2011). Decadal climate prediction with the European centre for medium-range weather forecasts coupled forecast system: impact of ocean observations. *J. Geophys. Res.* 116:D19111. doi: 10.1029/2010JD015394

Domingues, C. M., and Palmer, M. D. (2015). The IQuOD initiative: towards an international quality- controlled ocean database. *CLIVAR Exchanges* 67, 38–40.

Dong, S., Volkov, D., Goni, G., Lumpkin, R., and Foltz, G. R. (2017). Near7surface salinity and temperature structure observed with dual-sensor drifters in the subtropical South Pacific. *J. Geophys. Res.* 122, 5952–5969. doi: 10.1002/2017jc012894

Donlon, C., Robinson, I., Casey, K. S., and Vazquez-Cuervo, J. (2007). The global ocean data assimilation experiment high-resolution sea surface temperature pilot project. *Bull. Am. Meteorol. Soc.* 88, 1197–1214. doi: 10.1175/bams-88-8-1197

Donlon, C. J., Minnett, P. J., Gentemann, C., and Nightingale, T. J. (2002). Toward improved validation of satellite sea surface skin temperature measurements for climate research. *J. Clim.* 15, 353–369. doi: 10.1175/1520-0442(2002)015<0353:tivoss>2.0.co;2

d'Orgeville, M., and Peltier, W. R. (2007). On the pacific decadal oscillation and the atlantic multidecadal oscillation: might they be related? *Geophys. Res. Let.* 34:L23705. doi: 10.1029/2007GL031584

Durack, P. J., Lee, T., Vinogradova, N. T., and Stammer, D. (2016). Keeping the lights on for global ocean salinity observation. *Nat. Clim. Change* 6, 228–231. doi: 10.1038/nclimate2946

Edwards, C. A., Moore, A. M., Hoteit, I., and Cornuelle, B. D. (2015). Regional ocean data assimilation. *Annu. Rev. Mar. Sci.* 7, 6.1–6.22.

Evensen, G. (2003). The Ensemble Kalman filter: theoretical formulation and practical implementation. *Ocean Dyn.* 53, 343–367. doi: 10.1007/s10236-003-0036-9

Feng, M., Zhang, X., Oke, P., Monselesan, D., Chamberlain, M., Matear, R., et al. (2016). Invigorating ocean boundary current systems around Australia during 1979-2014 – as simulated in a near-global eddy-resolving ocean model. *J. Geophys. Res.* 121, 3395–3408. doi: 10.1002/2016JC011842

Fenty, I., and Heimbach, P. (2013). Coupled sea ice–ocean-state estimation in the labrador sea and baffin bay. *J. Phys. Oceanogr.* 43, 884–904. doi: 10.1175/JPO-D-12-065.1

Ferry, N., Parent, L., Garric, G., Barnier, B., Jourdain, N. C., and the Mercator Team. (2010). Mercator global eddy permitting ocean reanalysis GLORYS1V1: description and results. *Mercator. Newslett.* 36, 15–27.

Ferry, N., Rémy, E., Brasseur, P., and Maes, C. (2007). The Mercator global ocean operational analysis system: assessment and validation of an 11-year reanalysis. *J. Mar. Syst.* 65, 540–560. doi: 10.1016/j.jmarsys.2005.08.004

Folland, C. K., and Parker, D. E. (1995). Correction of instrumental biases in historical sea surface temperature data. *Q. J. R. Meteorol. Soc.* 121, 319–367. doi: 10.1002/qj.49712152206

Ford, D., and Barciela, R. (2017). Global marine biogeochemical reanalyses assimilating two different sets of merged ocean colour products. *Remote Sens. Environ.* 203, 40–54. doi: 10.1016/j.rse.2017.03.040

Forget, G., Campin, J. M., Heimbach, P., Hill, C. N., Ponte, R. M., and Wunsch, C. (2015). ECCO version 4: an integrated framework for non-linear inverse modeling and global ocean state estimation. *Geosci. Model Dev.* 8, 3071–3104. doi: 10.5194/gmd-8-3071-2015

Fujii, Y., Cummings, J., Xue, Y., Schiller, A., Lee, T., Balmaseda, M. A., et al. (2015). Evaluation of the tropical pacific observing system from the ocean data assimilation perspective. *Q. J. R. Meteorol. Soc.* 141, 2481–2496. doi: 10.1002/qj.2579

Fuiji, Y. (2019). Observing system evaluation based on ocean data assimilation and prediction systems: on-going challenges and future vision for designing/supporting ocean observational networks. *Front. Mar. Sci.* (accepted).

Garric, G., Parent, L., Greiner, E., Drévillon, M., Hamon, M., Lellouche, J., et al. (2018). "Performance and quality assessment of the global ocean eddy-permitting physical reanalysis GLORYS2V4. Operational oceanography serving sustainable marine development," in *Proceedings of the Eight EuroGOOS International Conference*, Bergen.

Gentemann, C. L., and Akella, S. (2018). Evaluation of NASA GEOS7ADAS modeled diurnal warming through comparisons to SEVIRI and AMSR2 SST observations. *J. Geophys. Res.* 123, 1364–1375. doi: 10.1002/2017JC013186

Giese, B. S., Seidel, H. F., Compo, G. P., and Sardeshmukh, P. D. (2016). An ensemble of ocean reanalyses for 1815–2013 with sparse observational input. *J. Geophys. Res. Oceans* 121, 6891–6910. doi: 10.1002/2016JC012079

Gregg, W. W., Rousseaux, C. S., and Franz, B. A. (2017). Global trends in ocean phytoplankton: a new assessment using revised ocean colour data. *Remote Sens. Lett.* 8, 1102–1111. doi: 10.1080/2150704X.2017.1354263

Hackert, E., Ballabrera-Poy, J., Busalacchi, A. J., Zhang, R.-H., and Murtugudde, R. (2011). Impact of sea surface salinity assimilation on coupled forecasts in the tropical Pacific. *J. Geophys. Res. Oceans* 116:C05009. doi: 10.1029/2010JC006708

Hackert, E., Busalacchi, A. J., and Ballabrera-Poy, J. (2014). Impact of Aquarius sea surface salinity observations on coupled forecasts for the tropical Indo-Pacific Ocean. *J. Geophys. Res.* 119, 4045–4067. doi: 10.1002/2013JC009697

Haid, V., Iovino, D., and Masina, S. (2017). Impacts of freshwater changes on Antarctic sea ice in an eddy-permitting sea-ice–ocean model. *Cryosphere* 11, 1387–1402. doi: 10.5194/tc-11-1387-2017

Heimbach, P., Fukumori, I., Hill, C. N., Ponte, R. M., Stammer, D., Wunsch, C., et al. (2019). Putting it all together: adding value to the global ocean and climate observing systems with complete self-consistent ocean state and parameter estimates. *Front. Mar. Sci.* 6:55. doi: 10.3389/fmars.2019.00055

Hoskins, B. (2013). The potential for skill across the range of the seamless weather7climate prediction problem: a stimulus for our science. *Q. J. R. Meteorol. Soc.* 139, 573–584. doi: 10.1002/qj.1991

Hoteit, I., Luo, X., Bocquet, M., Kohl, A., and Eit-El-Fquih, B. (2018). "Data assimilation in oceanography: current status and new directions," in *New Frontiers in Operational Oceanography*, eds E. Chassignet, A. Pascual, J. Tintore, and J. Verron (Scotts Valley, CA: CreateSpace Independent Publishing Platform).

Ignatov, A., Zhou, X., Petrenko, B., Liang, X., Kihai, Y., Dash, P., et al. (2016). AVHRR GAC SST reanalysis version 1 (RAN1). *Remote Sens.* 8:315. doi: 10.3390/rs8040315

Juricke, S., MacLeod, D., Weisheimer, A., Zanna, L., and Palmer, T. (2018). "Seasonal to annual ocean forecasting skill and the role of model and observational uncertainty," in *Proceedings 20th conference EGU General Assembly, EGU2018*, Vienna.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., et al. (1996). The NCEP/NCAR 40- year reanalysis project. *Bull. Amer. Meteor. Soc.* 77, 437–471.

Kawai, Y., and Wada, A. (2007). Diurnal sea surface temperature variation and its impact on the atmosphere and ocean: a review. *J. Oceanogr.* 63, 721–744. doi: 10.1007/s10872-007-0063-0

Kazumori, M., Geer, A. J., and English, S. J. (2016). Effects of all7sky assimilation of GCOM7 W/AMSR2 radiances in the ECMWF numerical weather prediction system. *Q. J. R. Meteorol. Soc.* 142, 721–737. doi: 10.1002/qj.2669

Kennedy, J. J. (2014). A review of uncertainty in in situ measurements and data sets of sea surface temperature. *Rev. Geophys.* 52, 1–32. doi: 10.1002/2013RG000434

Kimmritz, M., Counillon, F., Bitz, C. M., Massonnet, F., Bethke, I., and Gao, Y. (2018). Optimising assimilation of sea ice concentration in an Earth system model with a multicategory sea ice model. *Tellus* 2018:1435945.

Kirtman, B., Power, S. B., Adedoyin, J. A., Boer, G. J., Bojariu, R., Camilloni, I., et al. (2013). in *Near-term Climate Change: Projections and Predictability. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, et al. (Cambridge: Cambridge University Press).

Köhl, A. (2015). Evaluation of the GECCO2 ocean synthesis: transports of volume, heat, and freshwater in the Atlantic. *Q. J. R. Meteorol. Soc.* 141, 166–181. doi: 10.1002/qj.2347

Laloyaux, P., de Boisseson, E., Balmaseda, M., Bidlot, J. R., Broennimann, S., Buizza, R., et al. (2018a). CERA-20C: a coupled reanalysis of the twentieth century. *J. Adv. Model. Earth Syst.* 10, 1172–1195. doi: 10.1029/2018MS001273

Laloyaux, P., Frolov, S., Ménétrier, B., and Bonavita, M. (2018b). Implicit and explicit cross correlations in coupled data assimilation. *Q. J. R. Meteorol. Soc.* 144, 1851–1863. doi: 10.1002/qj.3373

Lea, D. J., Drecourt, J., Haines, K., and Martin, M. J. (2008). Ocean altimeter assimilation with observational and model-bias correction. *Q. J. R. Meteorol. Soc.* 134, 1761–1774. doi: 10.1002/qj.320

Lea, D. J., Martin, M. J., King, R. R., Hines, A., Walters, D., and Thurlow, M. (2015). Assessing a new coupled data assimilation system based on the Met Office coupled atmosphere–land–ocean–sea ice model. *Mon. Weather Rev.* 143, 4678–4694. doi: 10.1175/MWR-D-15-0174.1

Lea, D. J., Martin, M. J., and Oke, P. R. (2013). Demonstrating the complementarity of observations in an operational ocean forecasting system. *Q. J. R. Meteorol. Soc.* 140, 2037–2049. doi: 10.1002/qj.2281

Lea, D. J., Martin, M. J., and Oke, P. R. (2014). Demonstrating the complementarity of observations in an operational ocean forecasting system. *Q. J. R. Meteorol. Soc.* 140, 2037–2049. doi: 10.1002/qj.2281

Legler, D. M., Freeland, H. J., Lumpkin, R., Ball, G., McPhaden, M. J., North, S., et al. (2015). The current status of the real-time *in situ* global ocean observing system for operational oceanography. *J. Operat. Oceanogr.* 8, 189–200. doi: 10.1080/1755876X.2015.1049883

Liang, X., and Yu, L. (2016). Variations of the global net air–sea heat flux during the "Hiatus" period (2001–10). *J. Clim.* 29, 3647–3660. doi: 10.1175/JCLI-D-15-0626.1

Lindsay, R., Wensnahan, M., Schweiger, A., and Zhang, J. (2014). Evaluation of seven different atmospheric reanalysis products in the Arctic. *J. Clim.* 27, 2588–2606. doi: 10.1175/jcli-d-13-00014.1

Maes, C., Reul, N., Behringer, D., and O'Kane, T. J. (2014). The salinity signature of the equatorial Pacific cold tongue as revealed by the satellite SMOS mission. *Geosci. Lett.* 1:17.

Martin, M., Dash, P., Ignatov, A., Banzon, V., Beggs, H., Brasnett, B., et al. (2012). Group for high resolution sea surface temperature (GHRSST) analysis fields inter-comparisons. *Part* 1: a GHRSST multi-product ensemble (GMPE). *Deep Sea Res. Part II: Top. Stud. Oceanogr.* 77, 21–30. doi: 10.1016/j.dsr2.2012.04.013

Martin, M. J., Balmaseda, M., Bertino, L., Brasseur, P., and Brassington, G. (2015). Status and future of data assimilation in operational oceanography. *J. Operat. Oceanogr.* 8, s28–s48. doi: 10.1080/1755876X.2015.1022055

Martin, M. J., King, R. R., While, J., and Aguiar, A. B. (2019). Assimilating satellite sea-surface salinity data from SMOS, Aquarius and SMAP into a global ocean forecasting system. *Q. J. R. Meteorol. Soc.* 145, 705–726. doi: 10.1002/qj.3461

Masina, S., Storto, A., Ferry, N., Valdivieso, M., Haines, K., Balmaseda, M., et al. (2017). An ensemble of eddy-permitting global ocean reanalyses from the MyOcean project. *Clim. Dyn.* 49, 813–841. doi: 10.1007/s00382-015-2728-5

Mason, P. J., Zillman, J. W., Simmons, A., Lindstrom, E. J., Harrison, D. E., Dolman, H., et al. (2010). *Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (2010 Update)*. Geneva: WMO.

Mazloff, M. R., Cornuelle, B. D., Gille, S. T., and Verdy, A. (2018). Correlation lengths for estimating the large-scale carbon and heat content of the southern ocean. *J. Geophys. Res.* 123, 883–901. doi: 10.1002/2017jc013408

McPhaden, M. J. (1995). The tropical atmosphere ocean (TAO) array is completed. *Bull. Am. Meteorol. Soc.* 76, 739–741.

McPhaden, M. J., Busalacchi, A. J., and Anderson, D. L. T. (2010). A TOGA retrospective. *Oceanography* 23, 86–103. doi: 10.5670/oceanog.2010.26

Meehl, G. A., Goddard, L., Boer, G., Burgman, R., Branstator, G., Cassou, C., et al. (2014). Decadal climate prediction: an update from the trenches. *Bull. Amer. Meteorol. Soc.* 95, 243–267.

Meehl, G. A., Goddard, L., Murphy, J., Stouffer, R. J., Boer, G., Danabasoglu, G., et al. (2009). Decadal prediction: can it be skillful? *Bull. Am. Meteorol. Soc.* 90, 1467–1485.

Mignac, D., Ferreira, D., and Haines, K. (2018). South Atlantic meridional transports from NEMO-based simulations and reanalyses. *Ocean Sci.* 14, 53–68. doi: 10.5194/os-14-53-2018

Moore, A. M., Martin, M. J., Akella, S. R., Arango, H. G., Balmaseda, M. A. A., Bertino, L., et al. (2019). Synthesis of ocean observations using data assimilation for operational, real-time and reanalysis systems: a more complete picture of the state of the ocean. *Front. Mar. Sci.* 6. doi: 10.3389/fmars.2019.00090

National Academies of Sciences, Engineering,, and Medicine [NASEM] (2018). *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space*. Washington, DC: The National Academies Press.

National Academies of Sciences, Engineering, and Medicine [NASEM] (2017). *Sustaining Ocean Observations to Understand Future Changes in Earth's Climate*. Washington, DC: The National Academies Press.

O'Kane, T. J., Sandery, P. A., Monselesan, D. P., Sakov, P., Chamberlain, M. A., Matear, R. J., et al. (2018). Coupled data assimilation and ensemble initialization with application to multi-year ENSO prediction. *J. Clim.* 32, 997–1024.

Oke, P. R., Brassington, G. B., Griffin, D. A., and Schiller, A. (2008). The bluelink ocean data assimilation system (BODAS). *Ocean Model.* 20, 46–70. doi: 10.1016/j.ocemod.2007.11.002

Oke, P. R., and Griffin, D. A. (2011). The cold-core eddy and strong upwelling off the coast of New South Wales in early 2007. *Deep Sea Res.* 58, 574–591. doi: 10.1016/j.dsr2.2010.06.006

Oke, P. R., Larnicol, G., Fujii, Y., Smith, G. C., Lea, D. J., Guinehut, S., et al. (2015a). Assessing the impact of observations on ocean forecasts and reanalyses: part 1, global studies. *J. Oper. Oceanogr.* 8, s49–s62. doi: 10.1080/1755876x.2015.1022067

Oke, P. R., Larnicol, G., Jones, E. M., Kourafalou, V., Sperrevik, A. K., Carse, F., et al. (2015b). Assessing the impact of observations on ocean forecasts and reanalyses: part 2, regional applications. *J. Oper. Oceanogr.* 8, s63–s79. doi: 10.1080/1755876x.2015.1022080

Oke, P. R., Sakov, P., Cahill, M. L., Dunn, J. R., Fiedler, R., Griffin, D. A., et al. (2013). Towards a dynamically balanced eddy-resolving ocean reanalysis: BRAN3. *Ocean Modelling* 67, 52–70. doi: 10.1016/j.ocemod.2013.03.008

Oke, P. R., Schiller, A., Griffin, G. A., and Brassington, G. B. (2005). Ensemble data assimilation for an eddy- resolving ocean model. *Q. J. R. Meteorol. Soc.* 131, 3301–3311. doi: 10.1256/qj.05.95

Palmer, M. D., Roberts, C. D., Balmaseda, M., Chang, Y.-S., Chepurin, G., Ferry, N., et al. (2017). Ocean heat content variability and change in an ensemble of ocean reanalyses. *Clim. Dyn.* 49, 909–930. doi: 10.1007/s00382-015-2801-0

Penny, S. G. (2017). Mathematical foundations of hybrid data assimilation from a synchronization perspective. *Chaos* 27:126801. doi: 10.1063/1.5001819

Penny, S. G., Akella, S., Alves, O., Bishop, C., Buehner, M., Chevallier, M., et al. (2017). *Coupled Data Assimilation for Integrated Earth System Analysis and Prediction: Goals, Challenges and Recommendations*. Geneva: World Meteorological Organization.

Penny, S. G., Bach, E., Bhargava, K., Chang, C.-C., Da, C., Sun, L., et al. (2019). Strongly coupled data assimilation in multiscale media: experiments using a quasi-geostrophic coupled model. *J. Adv. Model Earth Syst.* 11. doi: 10.1029/2019MS001652

Penny, S. S., Behringer, D. W., Carton, J. A., and Kalnay, E. (2015). A hybrid global ocean data assimilation system at NCEP. *Mon. Weather Rev.* 143, 4660–4677. doi: 10.1063/1.5001819

Perruche, C., Albert, A., and Drillet, Y. (2017). "PISCES biogeochemical reanalysis," in *Proceedings of the ERA-CLIM2 3rd General Assembly*, Vienna.

Piecuch, C. G., Ponte, R. M., Little, C. M., Buckley, M. W., and Fukumori, I. (2017). Mechanisms underlying recent decadal changes in subpolar North Atlantic Ocean heat content. *J. Geophys. Res.* 122, 7181–7197. doi: 10.1002/2017JC012845

Poli, P., Hersbach, H., Tan, D. G. H., Dee, D. P., Thépaut, J.-N., Simmons, A., et al. (2013). *The Data Assimilation System and Initial Performance Evaluation of the ECMWF Pilot Reanalysis of the 20th-Century Assimilating Surface Observations Only (ERA-20C)*. Reading: ECMWF.

Reynolds, R. W., Smith, T. M., Liu, C., and Chelton, D. B. (2007). Daily high-resolution-blended analyses for sea surface temperature. *J. Clim.* 20, 5473–5496. doi: 10.1175/2007jcli1824.1

Rosso, I., Mazloff, M. R., Verdy, A., and Talley, L. D. (2017). Space and time variability of the Southern Ocean carbon budget. *J. Geophys. Res.* 122, 7407–7432. doi: 10.1002/2016JC012646

Saha, S., Moorthi, S., Pan, H.-L., Wu, X., Wang, J., Nadiga, S., et al. (2010). The NCEP climate forecast system reanalysis. *Bull. Amer. Meteor. Soc.* 91, 1015–1057. doi: 10.1175/2010BAMS3001.1

Saha, S., Moorthi, S., Wu, X., Wang, J., Nadiga, S., Tripp, P., et al. (2014). The NCEP climate forecast system version 2 journal of climate. *J. Clim.* 27, 2185–2208. doi: 10.1175/JCLI-D-12-00823.1

Saji, N., Goswami, H. B. N., Vinayachandran, P. N., and Yamagata, T. (1999). A dipole mode in the tropical indian ocean. *Nature* 401, 360–363. doi: 10.1038/43854

Sakov, P., Counillon, F., Bertino, L., Lister, K. A., Oke, P. R., and Korablev, A. (2012). TOPAZ4 an ocean-sea ice data assimilation system for the North Atlantic and Arctic. *Ocean Sci.* 8, 633–656. doi: 10.5194/os-8-633-2012

Scaife, A. A., Arribas, A., Blockley, E., Brookshaw, A., Clark, R. T., Dunstone, N., et al. (2014). Skillful long-range prediction of European and North American winters. *Geophys. Res. Lett.* 41, 2514–2519. doi: 10.1002/2014GL059637

Schepers, D., de Boisséson, E., Eresmaa, R., Lupu, C., and de Rosnay, P. (2018). CERA-SAT: a coupled satellite-era reanalysis. *ECMWF Newslett.* 155, 32–37. doi: 10.21957/sp619ds74g

Schiller, A., and Oke, P. R. (2015). Dynamics of ocean surface mixed layer variability in the Indian Ocean. *J. Geophys. Res.* 120, 4162–4186. doi: 10.1002/2014JC010538

Schroeder, I. D., Santora, J. A., Bograd, S. J., Hazen, E. L., Sakuma, K. M., Moore, A. M., et al. (2017). Source water variability as a driver of rockfish recruitment in the California Current ecosystem. *Can. J. Fish. Aquat. Sci.* 27, R1206–R1208.

Schroeder, I. D., Santora, J. A., Moore, A. M., Edwards, C. A., Fiechter, J., Hazen, E., et al. (2014). Application of a data-assimilative regional ocean modeling system for assessing California Current System ocean conditions, krill, and juvenile rockfish interannual variability. *Geophys. Res. Lett.* 41, 5942–5950. doi: 10.1002/2014gl061045

Seelanki, V., Sreenivas, P., and Prasad, K. V. S. R. (2018). Impact of Aquarius sea-surface salinity assimilation in improving the ocean analysis over Indian Ocean. *Mar. Geodesy* 41, 144–158. doi: 10.1080/01490419.2017.1422817

SIPv4 (2017). *Strategic Implementation Plan (SIP) for Evolution of NGGPS to a National Unified Modeling System Version 4*. Available at: https://www.weather.gov/media/sti/nggps/Presentations%202017/Implementation/SIP-FY18-20-v4.pdf (accessed December 5, 2017).

Skofronick-Jackson, G., Kirschbaum, D., Petersen, W., and Huffman, G. (2018). The global precipitation measurement (GPM) mission's scientific achievements and societal contributions: reviewing four years of advanced rain and snow observations. *Q. J. R. Meteorol. Soc.* 144, 27–48. doi: 10.1002/qj.3313

Sluka, T. C. (2018). *Strongly Coupled Ocean-Atmosphere Data Assimilation With the Local Ensemble Transform Kalman Filter*. Ph.D. Dissertation, University of Maryland, Maryland.

Sluka, T. C., Penny, S. G., Kalnay, E., and Miyoshi, T. (2016). Assimilating atmospheric observations into the ocean using strongly coupled ensemble data assimilation. *Geophys. Res. Lett.* 43, 752–759. doi: 10.1002/2015GL067238

Smith, D. M., Scaife, A. A., and Kirtman, B. (2012). What is the current state of scientific knowledge with regard to seasonal and decadal forecasting. *Environ. Res. Lett.* 7:015602. doi: 10.1088/1748-9326/7/1/015602

Song, H., Edwards, C., Moore, A. M., and Fiechter, J. (2016). Data assimilation in a coupled physical- biogeochemical model of the California Current System using an incremental lognormal 4- dimensional variational approach: part 3, Assimilation in a realistic context using satellite and in situ observations. *Ocean Model.* 106, 159–172. doi: 10.1016/j.ocemod.2016.06.005

Stammer, D., Balmaseda, M., Heimbach, P., Köhl, A., and Weaver, A. (2016). Ocean data assimilation in support of climate applications: status and perspectives. *Ann. Rev. Mar. Sci.* 8, 491–518. doi: 10.1146/annurev-marine-122414-034113

Stammer, D., Ueyoshi, K., Köhl, A., Large, W. G., Josey, S. A., and Wunsch, C. (2004). Estimating air-sea fluxes of heat, freshwater, and momentum through global ocean data assimilation. *J. Geophys. Res.* 109, C05023. doi: 10.1029/2003JC002082

Stark, J. D., Donlon, C. J., Martin, M. J., and McCulloch, M. E. (2007). "OSTIA: an operational, high resolution, real time, global sea surface temperature analysis system," in *Proceedings of the Oceans 07 Conference Marine Challenges: Coastline to Deep Sea*, (Aberdeen: IEEE).

Stockdale, T. N., Balmaseda, M. A., Johnson, S., Ferranti, L., Molteni, F., and Magnusson, L. (2018). *SEAS5 and the Future Evolution of the Long-Range Forecasting System*. Reading: ECMWF Technical Memorandum.

Storto, A., and Masina, S. (2016). C-GLORSv5: an improved multipurpose global ocean eddy-permitting physical reanalysis. *Earth Syst. Sci. Data* 8, 679–696. doi: 10.5194/essd-8-679-2016

Storto, A., Masina, S., and Navarra, A. (2016a). Evaluation of the CMCC eddy7permitting global ocean physical reanalysis system (C7GLORS, 1982–2012) and its assimilation components. *Q. J. R. Meteorol. Soc.* 142, 738–758. doi: 10.1002/qj.2673

Storto, A., Yang, C., and Masina, S. (2016b). Sensitivity of global ocean heat content from reanalyses to the atmospheric reanalysis forcing: a comparative study. *Geophys. Res. Lett.* 43, 5261–5270. doi: 10.1002/2016GL068605

Sugiura, N., Awaji, T., Masuda, S., Mochizuki, T., Toyoda, T., Miyama, T., et al. (2008). Development of a four-dimensional variational coupled data assimilation system for enhanced analysis and prediction of seasonal to interannual climate variations. *J Geophys. Res.* 113:C10017. doi: 10.1029/2008JC004741

Takaya, Y., Bidlot, J. R., Beljaars, A., and Janssen, P. A. (2010). Refinements to a prognostic scheme of skin sea surface temperature. *J. Geophys. Res.* 115:C06009.

The European Environment Agency [EEA] (2017). *State of Play ReportEEA/IDM/15/026/. (LOT1).* Available at: https://insitu.copernicus.eu/library/reports/state-of-play-report-observations-december-2017-2 (accessed November 28, 2017).

The IQuOD Team (2018). *International Quality Controlled Ocean Database (IQuOD) version 0.1 - aggregated and community quality controlled ocean profile data 1772-2018 (NCEI Accession 0170893). Version 1.1*. Silver Spring: NOAA.

Timmermann, A., An, S. I., Kug, J. S., Jin, F. F., Cai, W., Capotondi, A., et al. (2018). El Niño–Southern Oscillation complexity. *Nature* 559, 535–545.

Toyoda, T., Fujii, Y., Yasuda, T., Usui, N., Ogawa, K., Kuragano, T., et al. (2016). Data assimilation of sea ice concentration into a global ocean-sea ice model with corrections for atmospheric forcing and ocean temperature fields. *J. Oceanogr.* 72, 235–262. doi: 10.1007/s10872-015-0326-0

Tranchant, B., Remy, E., Greiner, E., and Legalloudec, O. (2018). Data assimilation of SMOS observations into the Mercator Ocean operational system: focus on the Nino 2015 event. *Ocean Sci. Discuss.* 15, 543–563. doi: 10.5194/os-2018-113

Uotila, P., Goosse, H., Haines, K., Chevallier, M., Barthelemy, A., Bricaud, C., et al. (2018). An assessment of ten ocean reanalyses in the polar regions. *Clim. Dyn.* 52, 1613–1650. doi: 10.1007/s00382-018-4242-z

Usui, N., Wakamatsu, T., Tanaka, Y., Hirose, N., Toyoda, T., Nishikawa, S., et al. (2017). Four- dimensional variational ocean reanalysis: a 30-year high-resolution dataset in the western North Pacific (FORA-WNP30). *J. Oceanogr.* 73, 205–233. doi: 10.1007/s10872-016-0398-5

Valdivieso, M., Haines, K., Zuo, H., and Lea, D. (2014). Freshwater and heat transports from global ocean synthesis. *J. Geophys. Res. Oceans* 119, 394–409. doi: 10.1002/2013JC009357

Verdy, A., and Mazloff, M. R. (2017). A data assimilating model for estimating Southern Ocean biogeochemistry. *J. Geophys. Res.* 122, 6968–6988. doi: 10.1002/2016JC012650

Vernieres, G., Kovach, R., Keppenne, C., Akella, S., Brucker, L., and Dinnat, E. (2014). The impact of the assimilation of Aquarius sea surface salinity data in the GEOS Ocean Data Assimilation System. *J. Geophys. Res.* 119, 6974–6987. doi: 10.1002/2014JC010006

Verrier, S., Le Traon, P.-Y., and Remy, E. (2017). Assessing the impact of multiple altimeter missions and Argo in a global eddy-permitting data assimilation system. *Ocean Sci.* 13, 1077–1092. doi: 10.5194/os-13-1077-2017

Vinogradova, N. T., Lee, T. H., Boutin, J., Drushka, K., Fournier, S., Sabia, R., et al. (2019). Satellite salinity observing system: recent discoveries and the way forward. *Front. Mar. Sci.* (in press). doi: 10.3389/fmars.2019.00243

Vitart, F., Ardilouze, C., Bonet, A., Brookshaw, A., Chen, M., Codorean, C., et al. (2017). The Subseasonal to Seasonal (S2S) Prediction Project Database. *Bull. Amer. Meteor. Soc.* 98, 163–173. doi: 10.1175/BAMS-D-16-0017.1

Vitart, F., Balsamo, G., Buizza, R., Ferranti, L., Keeley, S., Magnusson, L., et al. (2014). "Sub-seasonal predictions," in *Paper Presented ECMWF Technical Memorandum, Special Topic Paper on Sub- Seasonal Predictions Presented at the 43rd ECMWF Scientific Advisory Committee*, Reading.

Vitart, F., Robertson, A., and the S2S steering group (2015). *Sub-Seasonal to Seasonal Prediction: Linking Weather and Climate. Seamless Prediction of the Earth System: From Minutes to Months*. Geneva: WMO.

Vitart, F., and Robertson, A. W. (2018). The sub-seasonal to seasonal prediction project (S2S) and the prediction of extreme events. *Clim. Atmos. Sci.* 1:3. doi: 10.3390/ijerph13020206

Volz, S., Maier, M., and Di Pietro, D. (2016). "The NOAA Satellite Observing System Architecture study," in *Proceedings of the 2016 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, Beijing.

Waliser, D. E. (2011). in *Predictability and Forecasting. Intraseasonal Variability of the Atmosphere-Ocean Climate System*, eds W. K. M. Lau and D. E. Waliser (Heidelberg: Springer).

Wang, C. (2005). "ENSO, Atlantic climate variability, and the Walker and Hadley circulations," in *The Hadley Circulation: Present, Past, and Future*, eds H. F. Diaz and R. S. Bradley (Dordrecht: Kluwer Academic Publishers), 173–202. doi: 10.1007/978-1-4020-2944-8_7

Waters, J., Bell, M. J., Martin, M. J., and Lea, D. J. (2017). Reducing ocean model imbalances in the equatorial region caused by data assimilation. *Q. J. R. Meteorol. Soc.* 143, 195–208. doi: 10.1002/qj.2912

Webster, P. J., Moore, A. M., Loschnigg, J. P., and Leben, R. P. (1999). Coupled ocean–atmosphere dynamics in the Indian Ocean during 1997–98. *Lett. Nat.* 401, 356–360. doi: 10.1038/43848

Woolnough, S. J., Vitart, F., and Balmaseda, M. A. (2007). The role of the ocean in the Madden-Julian oscillation: implications for the MJO prediction. *Q. J. R. Meteorol. Soc.* 133, 117–128. doi: 10.1002/qj.4

Wu, R., Kirtman, B. P., and van den Dool, H. (2009). An analysis of ENSO prediction skill in the CFS retrospective forecasts. *J. Clim.* 22, 1801–1818. doi: 10.1175/2008JCLI2565.1

Wunsch, C., and Heimbach, P. (2013). "Dynamically and kinematically consistent global ocean circulation and ice state estimates," in *Ocean Circulation and Climate - A 21st Century Perspective", International Geophysics Series*, Vol. 103, eds G. Sielder, J. Church, S. Griffes, J. Gould, and J. Church (Cambridge: Academic Press).

Wunsch, C., and Heimbach, P. (2014). Bidecadal thermal changes in the Abyssal Ocean. *J. Phys. Oceanogr.* 44, 2013–2030. doi: 10.1175/JPO-D-13-096.1

Xue, Y., Huang, B., Hu, Z. Z., Kumar, A., Wen, C., Behringer, D., et al. (2011). An assessment of oceanic variability in the NCEP climate forecast system reanalysis. *Clim. Dyn.* 37, 2511–2539. doi: 10.1007/s00382-010-0954-4

Xue, Y., Wen, C., Kumar, A., Balmaseda, M., Fujii, Y., Alves, O., et al. (2017). A real-time ocean reanalyses intercomparison project in the context of tropical pacific observing system and ENSO monitoring. *Clim. Dyn.* 49, 3647–3672. doi: 10.1007/s00382-017-3535-y

Yang, C., Masina, S., and Storto, A. (2017). Historical ocean reanalyses (1900–2010) using different data assimilation strategies. *Q. J. R. Meteorol. Soc.* 143, 479–493. doi: 10.1002/qj.2936

Yang, C., Storto, A., and Masina, S. (2018). Quantifying the effects of observational constraints and uncertainty in atmospheric forcing on historical ocean reanalyses. *Clim. Dyn.* 52, 3321–3342. doi: 10.1007/s00382-018-4331-z

Yu, L. (2019). Global air-sea fluxes of heat fresh water, and momentum: energy budget closure and unanswered questions. *Ann. Rev. Mar. Sci.* 11, 227–248. doi: 10.1146/annurev-marine-010816-060704

Zampieri, L., Goessling, H. F., and Jung, T. (2018). Bright prospects for Arctic sea ice prediction on subseasonal time scales. *Geophys. Res. Lett.* 45, 9731–9738. doi: 10.1029/2018GL079394

Zhu, J., Huang, B., Zhang, R.-H., Hu, Z.-Z., Kumar, A., Balmaseda, M. A., et al. (2014). Salinity anomaly as a trigger for ENSO events. *Nat. Sci. Rep.* 4:6821. doi: 10.1038/srep06821

Zhu, Y., Zhou, X., Li, W., Hou, D., Melhauser, C., Sinsky, E., et al. (2018). Toward the improvement of subseasonal prediction in the National Centers for environmental prediction global ensemble forecast system. *J. Geophys. Res.* 123, 6732–6745. doi: 10.1029/2018JD028506

Zilberman, N. V. (2017). Deep Argo: sampling the total ocean volume in state of the climate in 2016. *Bull. Am. Meteorol. Soc.* 98, S73–S74. doi: 10.1175/2017BAMSStateoftheClimate.1

Zuo, H., Balmaseda, M. A., Boisseson, E., and Hirahara, S. (2017a). *A New Ensemble Generation Scheme for Ocean Reanalysis*. Reading: ECMWF.

Zuo, H., Balmaseda, M. A., and Mogensen, K. (2017b). The new eddy-permitting ORAP5 ocean reanalysis: description, evaluation and uncertainties in climate signals. *Clim. Dyn.* 49, 791–811. doi: 10.1007/s00382-015-2675-1

Zuo, H., Balmaseda, M. A., Mogensen, K., and Tietsche, S. (2018). *OCEAN5: The ECMWF Ocean Reanalysis System and its Real-Time Analysis Component*. Reading: ECMWF.

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frontiers in Marine Science

REVIEW
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Waves and Swells in High Wind and Extreme Fetches, Measurements in the Southern Ocean

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The generation and evolution of ocean waves by wind is one of the most complex phenomena in geophysics, and is of great practical significance. Predictive capabilities of respective wave models, however, are impaired by lack of field *in situ* observations, particularly in extreme Metocean conditions. The paper outlines and highlights important gaps in understanding the Metocean processes and suggests a major observational program in the Southern Ocean. This large, but poorly investigated part of the World Ocean is home to extreme weather around the year. The observational network would include distributed system of buoys (drifting and stationary) and autonomous surface vehicles (ASV), intended for measurements of waves and air-sea fluxes in the Southern Ocean. It would help to resolve the issues of limiting fetches, extreme Extra-Tropical cyclones, swell propagation and attenuation, wave-current interactions, and address the topics of wave-induced dispersal of floating objects, wave-ice interactions in the Marginal Ice Zone, Metocean climatology and its connection with the global climate.

Keywords: wind wave and swell, air-sea and air-sea-land interaction processes, wave fetch, extreme wave, extra-tropical anticyclones

INTRODUCTION

The generation and evolution of ocean waves by wind is one of the most complex phenomena in geophysics. Forecasting skill and understanding of these dynamics is critical across a wide range of oceanic applications, including maritime and coastal engineering, air-sea interactions, ocean dynamics, climate, remote sensing. However, the generation and evolution of waves in high-wind conditions and extreme fetches remains poorly understood.

Models are widely inconsistent for large fetch/duration conditions, to a significant extent due to lack of observational guidance. Extreme storms in the North Atlantic and Pacific are seasonal and diverse in their propagation which hinders systematic *in situ* observations in these regions (e.g., Meucci et al., 2018; Takbash et al., 2018). Also, they usually do not provide extreme fetches. Observations of high-wind conditions with extreme fetch, however, are possible in the Southern Ocean, where these conditions occur regularly and storms move in the same direction (West to East) throughout the year. Swell, which results from such storms in the Southern Ocean radiates into all major ocean basins, but remains poorly predicted by forecast models, both in magnitude and arrival time.

This paper proposes systematic *in situ* field observations in the Southern Ocean. Understanding the extreme fetch and forcing conditions, and respective advance of the wave models is possible through such observations conducted by means of deployment of a distributed buoy network (drifting and stationary) and autonomous surface vehicles (ASV) in the Southern Ocean. The buoys and ASVs could be deployed from ships of opportunity and through designated efforts of interested countries (e.g., Schulz et al., 2012).

Apart from the extreme fetch and swell problems, such an observational network in the Southern Ocean would address a number of Metocean topics that remain unresolved for decades. The Sections below cover the following unattended problems of Metocean conditions in the World Ocean:

- Wave evolution at extreme fetches;
- Severe extra-tropical cyclones at extreme fetches;
- Swell dynamics and forecasting, with attention to arrival time;
- Wave-driven dispersal of floating objects (search and rescue, transport of microplastic and other pollutants);
- Non-linear wave-current interactions;
- Wave-ice interactions in Marginal Ice Zone subject to extreme storms and waves;
- Metocean climatology in the Southern Ocean.

WAVE EVOLUTION AT EXTREME FETCHES

Following the classical paper by Pierson and Moskowitz (1964), it is commonly accepted that there is a limiting condition for wave development such that, for a given wind speed, the significant wave height H_s and peak wavelengths (periods) stop growing. In non-dimensional terms of mean wind speed at standard 10 m height U_{10} and phase speed of peak waves c_p, the limiting stage of wave development is described by ratio

$$U_{10}/c_p = 0.82 \tag{1}$$

which, basically, means that once the dominant waves in a wind-generated field (spectrum) are faster than the wind, the wave development ceases. While intuitively attractive, this concept does not necessarily agree with observations – for example, Young (2006) for Tropical Cyclones and Thomson and Rogers (2014) for lighter winds, demonstrated measurements of wind-generated waves well beyond the PM limit.

Thus, 50+ years after Pierson and Moskowitz, such limit is still in need of validation, clarification, understanding and explaining. While it was purely empirical concept originally, now we can speculate on such a limit from a more advanced physical perception of wind-wave evolution. Such perception includes non-linear interactions which have no regard for the wind and maintain the energy flux to low frequencies (i.e., wave periods larger than the spectral peak), provided the energy flux to the high frequencies continues (e.g., Zakharov and Zaslavskii, 1982). In principle, such behavior would signify no full development, but at some stage the very long waves would be so fast that the friction against the air (no matter how small it is), would balance the weakening non-linear energy influx [e.g., the mechanism for wind-wave interactions when waves overtake the wind in Donelan et al. (2012)].

Not surprisingly, in absence of clear physical guidance, performance of wave-forecast models in the context of full development is contradictory and far from being consistent. While typically tuned to the PM saturation in academic tests, the models hardly ever meet the limiting criteria in realistic simulations. In **Figure 1** such comparisons are reproduced from Rogers (2002), for three different physics packages: ST1, ST2, and WAM4, with the first two being from the WAVEWATCH-III model (WW3, Tolman, 2002). In all the cases the mean wind speed is U_{10} = 15 m/s which, if allowed to persist over unlimited fetch/duration, should lead to ultimate PM wave height of H_s = 5.5 m. None of the models do —they do not even come close — and none reaches another asymptote. This is also true of newer physics packages available in recent versions of WW3 (Wavewatch III® Development Group, 2016) – ST3, ST4, and ST6 (unpublished). Models in **Figure 1** are dissimilar, so at least two are wrong, and probably all three are wrong, but we note that the behavior simulated here is *unvalidated*, due to scarce observations. Such extreme fetch/duration is a primary "frontier" area for observations, associated with uncertainty in the models.

In principle, if quasi-full-development exists, it should be easier to reach for lower winds [albeit not in Thomson and Rogers (2014)] than for higher winds. It may never happen for high winds due to very long fetches required, but if it happens anywhere, it would be in the Southern Ocean where, depending on the speed of propagation of extra-tropical cyclones, the fetches can be virtually unlimited. The question of the full development is not hypothetical and/or of pure academic value and interest: lack of understanding of wave evolution at the extreme end of Metocean conditions and wave fetches imposes real limitation on performance of models in circumstances which are most critical for maritime engineering and operations.

Therefore, a network or array of wave buoys (or a set of drifting buoys) in east-west direction in the Southern Ocean would be able to prove or disprove the concept of fully developed limiting stage. Most importantly, such concept, intuitively

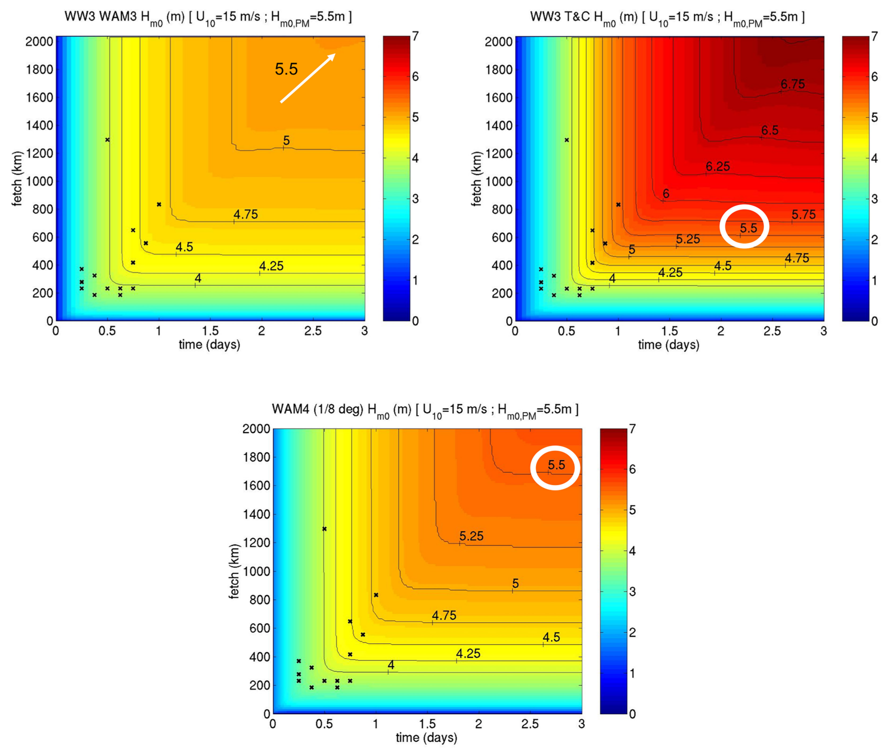

FIGURE 1 | Simulating the PM limit in WW3 (WAM3/ST1, WAM4, ST2 packages from left to right, respectively). U_{10} = 15 m/s corresponds to PM H_s = 5.5 m. Horizontal scale is duration of wave evolution in days, vertical scale is fetch in kilometers, and color scale is wave height in meters [Figure is reproduced from Rogers (2002)].

attractive and most like correct, needs quantification which is only possible on the basis of solid experimental evidence.

SEVERE EXTRA-TROPICAL CYCLONES AT EXTREME FETCHES

As a reference point for the extreme Metocean conditions, the hurricane-scale classification is often used: that is a tropical storm becomes a hurricane if the wind speed reaches $U_{10} \sim 33$ m/s. Babanin (2018) argued that such classification is not arbitrary, and indeed signifies change of physical regimes in all the three environments near the air-sea interface: in the atmospheric boundary layer, at the surface, and through the upper ocean. This threshold is approximately the wind speed at which the drag coefficient was found to saturate in the field observations [$U_{10} \approx$ 32–33 m/s, e.g., in Powell et al. (2003)]. This saturation has received a lot of attention lately. Less known are the *in situ* measurements below the surface, change of the upper-ocean mixing mechanism and of bubble dynamics occur at $U_{10} > 35$ m/s (McNeil and D'Asaro, 2007). Directly at the surface, wave dynamics also undergoes essential transformations, from wave breaking (dissipation) being driven by evolution of non-linear waves, to the breaking being forced directly by the winds, at $U_{10} \approx 34$ m/s [Babanin (2011) based on laboratory measurements of Leikin et al. (1995)]. Perhaps related to the wave-breaking change of mechanism is the most striking and abrupt alteration of the gas (CO_2) transfer at U_{10} = 33.6 m/s in laboratory experiments of Iwano et al. (2013). It is therefore argued that the simultaneous change of physical regime in all the three air-sea environments cannot be coincidental. Such change of the regime means that if we extrapolate our parameterisations from regular conditions into the extreme Metocean environments (which is what we usually do), we will obtain biased or even incorrect results.

It is easy to appreciate the significance of understanding and adequate modeling of waves in such conditions, both for practical and academic purposes, and the associated difficulties which to a large extent are due to lack of respective measurements. What is not appreciated, perhaps due to the lack of observations, is how different are the evolution of such waves in extreme Tropical (TC) and Extra-Tropical (ETC) cyclones. While the waves with H_s in excess of 15 m are not uncommon in both cases [e.g., Young (2006) for TC and Rapizo et al. (2015) for ETC] their directional spectra are very different. Young (2006) based on a large collection of directional spectra in tropical cyclones demonstrated that direction of peak waves does not follow the local wind and, at some quadrants of TCs can be at 90 and even 180 degrees to the wind, whereas in ETCs Rapizo et al. (2015) did not observe unexpected major deviations between wind and wave propagation angles. This means that, while wave evolution in ETC probably follows the direct wind-forcing pattern, in TCs this evolution is different. Young (2006) argued that the presence of large waves propagating perpendicular or even against the wind can only be explained due to the fact that their growth is controlled by non-linear interactions. If so, this is not just an academic curiosity: both the wave-growth dependences and asymptotic behaviors of respective waves will be different (Badulin et al., 2007).

Needless to say, that such differences are not validated and not even accounted for in the current wave forecast. While measurements in Tropical Cyclones are rare, the detailed and consistent measurements in Extreme-Tropical Cyclones are nearly absent. Dedicated effort in the Southern Ocean, where ETCs are continuously present around the year, would be the best observational ground for such extreme Metocean circumstances. Presently, there is only one flux station available at 47 degrees south, 142 degrees East [south of Tasmania Schulz et al. (2012)], and it is proposed that such stations, or air-sea interaction buoys, are deployed south of New Zealand, South America and South Africa. Autonomous surface vehicles (ASV), deployed from ships of opportunity or as a dedicated effort have also proved an efficient way of investigating the air-sea interactions in extreme weather (Schmidt et al., 2017; Thomson and Girton, 2017).

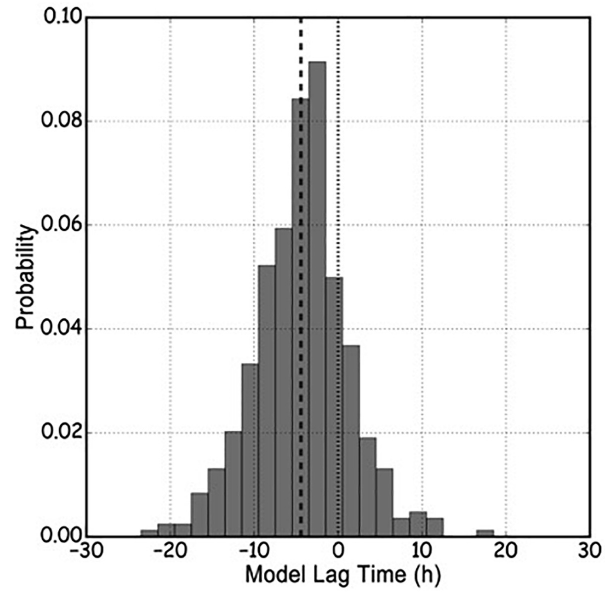

FIGURE 2 | Histogram of relative swell arrival time, model versus buoy observations. Negative values correspond to model predictions being early [Figure is reproduced from Babanin and Jiang (2017)].

SWELL DYNAMICS AND FORECASTING, WITH ATTENTION TO ARRIVAL TIME

Swell waves are present in most of ocean wave spectra (e.g., Semedo et al., 2011), and provide significant adverse impact on maritime operations and coastal inundation. Their prediction by wave-forecast models, however, is poor, both in terms of wave amplitude and, particularly, arrival time.

The third-generation models, until recently, have entirely based their physics on dynamics and interactions of wind-generated seas. In phenomenological terms, such models simulate the Radiative Transfer Equation [see, e.g., the state-of-the-art review by Cavaleri et al. (2007)]:

$$\frac{dE}{dt} = S_{in} + S_{ds} + S_{nl} \tag{2}$$

where E is wave spectrum, which changes in space and time and whose integral is the total wave energy, and the right-hand side are sources S_{in} (from the wind), sinks S_{ds} (usually due to wave breaking) and redistribution terms S_{nl} for this energy (more terms are available in specific circumstances, particularly in finite depths). While the forecast based on (2) is applied globally, none of the terms on the right, strictly speaking, applies to the swell: swell is not wind-forced (by definition), swell does not break in deep water because of its low steepness, and the Hasselmann resonant interactions usually employed as S_{nl} are not applicable to swells because they are unidirectional and therefore cannot satisfy the resonance conditions.

The very definition of ocean swell is ambiguous: while it is usually perceived as former wind-generated waves, in fact it may reconnect with the local wind through non-linear interactions. The visible swell attenuation is driven by a number of dissipative and non-dissipative processes. The dissipative phenomena include interaction with turbulence on the water and air sides (e.g., Babanin, 2006; Ardhuin et al., 2010), with adverse winds or currents (e.g., Donelan, 1999; Babanin et al., 2017, respectively). Non-dissipative contributions to the gradual decline of wave amplitude come from frequency dispersion and directional spreading, refraction by currents, and lateral diffraction of wave energy (e.g., respectively, Ardhuin et al., 2009; Babanin and Waseda, 2015; Rapizo et al., 2018). The interactions with local winds/waves can, on the contrary, cause swell growth (perhaps some observations by Ardhuin et al. (2009) fall into this category).

Swell arrival time is the least understood and the most uncertain problem. Joint analysis of buoy observations and model reanalysis shows that swell can be tens of hours early or late by comparison with model predictions (Jiang et al., 2016), see **Figure 2**. This is where the lack of model performance incurs the worst consequences: many practical applications related to swell depend not so much on swell height and steepness (which is usually low), but on its presence or absence (operating the tankers, dredging, ports).

Obviously, since the arrival-time error can be both negative and positive, no single physical mechanism can be held responsible for such failure to perform. Rather, this is a combination of various mechanisms, particularly as swells propagate very large distances over vast ocean surfaces and hence even a single swell event can be subject to multiple influences (Babanin and Jiang, 2017). Finite frequency resolution of the initial wave spectrum in a model can be a reason, randomly responsible for early/late arrival, albeit small. For the early arrival, swell has to be accelerating as it moves away from the distant source, such acceleration can be perceived (i.e., short wavelength decaying faster than the longer waves) or real. A real acceleration of waves can be caused, for example, by so-called Raman effect – downshift of wave energy due to modulational instability of non-linear waves in dispersive environments. This effect is well known in non-linear optics (e.g., Gordon, 1986), and has been perceived for the surface waves too (Segur et al., 2005). Interactions of swell with local winds, waves, currents, or a combination of those, can bring about a plethora of accelerating/decelerating effects. For example, adverse currents with horizontal velocity gradient instigate modulational instability and may lead to sudden frequency downshift and propagation acceleration (Babanin et al., 2011). Gradual decrease of wave steepness in the course of wave attenuation should cause slight deceleration of moving swells. Refraction of waves by currents and large-scale eddies, permanent and abundant in the Southern Ocean and at the periphery of other oceans, can bring refraction and sequence of divergence/convergence of swell rays, to result in larger propagation distances and later arrival (e.g., Rapizo et al., 2018). Waves can be trapped by the currents (e.g., Shrira and Slunyaev, 2014) which fact can cause either acceleration or deceleration. Influence of the vertical gradient of surface currents on kinematics of wave orbital motion is likely, but unknown. Shallows and islands, if encountered by swell on its path, should slow it down. Relative to the deep-water value, group velocity is increased in intermediate depth and reduced in shallow depths, and diffraction of waves into the island shade causes reduction of wave energy and hence the velocity.

Field observations of the swell dynamics, however, are even less frequent than those for waves in the tropical cyclones: the three papers by Snodgrass et al. (1966), Ardhuin et al. (2009), and Young et al. (2013) are perhaps close to the exhaustive list. Only the first paper is based on *in situ* measurements, and the modern studies are remote sensing. The satellites do provide global coverage in nearly real time and are an effective way of estimating swell decay, but they cross the great circles rather than follow swells and, as far as swell arrival time is concerned, in their measurements have to rely on assumptions on the swell propagation speeds, which fact is not helpful since these speeds obviously change as the swell propagates.

Thus, field *in situ* observations are critical for unveiling the very complex nature of swell problem. A majority of world's swells are produced by the Southern Ocean storms with its severe weather around the year which radiates swell waves across the Pacific, Indian and South Atlantic Oceans (Aguirre et al., 2017; Portilla-Yandún, 2018, among others). In this regard, it should also be pointed out that, even in its simplest scenario of swell propagation, the main uncertainties in description of swell propagation are within the proximity of ∼4000 km to its source storm (Ardhuin et al., 2009) which fact makes measurements of the Southern Ocean swells close to their origin critical for understanding their nature. Therefore, a network of wave buoys or systematic deployment of drifting wave buoys in the southern parts of the Pacific, Indian and Atlantic Oceans is proposed to address the problem.

WAVE-DRIVEN DISPERSAL OF FLOATING OBJECTS

The spreading of floating objects on the ocean surface is a fundamental problem of fluid mechanics which has a significant practical value, for marine search and rescue, dispersion of pollution. Note that, while mean drift by surface currents and large-scale eddies are well determined nowadays, particularly with implementation of satellite altimetry, random dispersion of surface drifters remains the open problem (e.g., Soomere et al., 2011). In this regard, the impact of ocean waves with random phases and directional spectrum, remains not accounted for or even well-perceived.

The aviation disaster of Malaysian Flight MH370 drew the public attention to the necessity and complexity of oceanic modeling. In particular, it highlighted the fact that, while modeling of the ocean currents is conducted at the top level, there is no coherent and coupled wave-current modeling. Wave orbital velocities can exceed the geostrophic or wind-driven surface currents, and furthermore wave-induced drift and currents can be comparable to the ocean currents, but are unrelated to them both in speed and direction, and therefore search of debris or missing-at-sea people days and even weeks after the incident are essentially impaired without the coupled wave-wind-current approach. Debris (and hence surface pollution and other floating objects) are carried by geostrophic currents, and by wave-induced currents (Stokes drift and momentum passed by wave breaking). The latter cannot be included on average because it is absent if there is no storm in the area and has to be a subject of new modeling development.

Additionally, random waves with directional spectrum would scatter the floating objects. Formally, turbulent dispersion of a passive tracer caused by a random wavefield is similar to the conventional mechanism of the Taylor dispersion (Batchelor and Townsend, 1956), i.e., particle dispersion by a "conventional" turbulent flow, but with the random velocity field is induced by ensemble of random waves (wave turbulence) and not by conventional turbulent flow. This imposes additional analytical and experimental challenges for investigation of this phenomena (e.g., Herterich and Hasselmann, 1982; Balk, 2001; Falkovich, 2009). In some way, this problem is similar to two-dimensional turbulence applications, and hence can borrow from turbulence research, but will also feed back to the fundamental science because the 2D turbulence has received far less attention than its 3D counterpart. And applications of random 2D vorticity, i.e., when vertical scales are much smaller than horizontal scales, range from boundary layers very near the surface to TCs and upper-ocean circulation.

Southern Ocean, if wave buoys with satellite tracking are released as drifters, is the natural body for introducing, developing, investigating, testing and validating the wave-dispersal theories, and implementing them in practice. Innovation due to introduction of the wave scattering can be as big as difference between finding and not finding MH370 and other subjects of search and rescue. Since debris of MH370 have been found along the African coast, location of their origin in the Southern Ocean will require solving the problem of inverse scattering, where new methodology can prove an innovation in its own right. Logistically, this important observational issue can be addresses through deployments of drifting wave buoys in the Southern Ocean as suggested in see Sections "Wave Evolution at Extreme Fetches" and "Severe Extra-Tropical Cyclones at Extreme Fetches."

NON-LINEAR WAVE-CURRENT INTERACTIONS

As far as ocean currents are concerned, these conditions are not common, but are not rare either. Major currents such as Gulf Stream, Kuroshio or Agulhas are well known for harsh seas and high likelihood of abnormal (rogue) waves. Tidal inlets with waves on strong and variable currents are a typical feature of shipping routes in coastal areas. Linear effects of currents on waves, such as refraction, Doppler shift or relative speed with respect to the wind are assumed to be implicitly or explicitly included in wave-forecast models. Our review indicated that in the framework of JCOMM/WMO, since 2001, there is a monthly intercomparison of operational wave model with buoys. Furthermore, operational wave model account for wave/currents interactions by using a surface currents forcing, like the global wave system implemented in Copernicus Marine Service.

Still, absolute majority of the buoys are not located in the Southern Ocean and even the central part of the Atlantic and the Pacific Ocean. So, the validation in the large parts of the ocean, especially at high sea states is mostly missing. Moreover, non-linear effects are usually left out or even unknown. These include changes to non-linear interactions in presence of currents with horizontal or vertical velocity gradients, wave/current energy and momentum exchanges, non-linear modifications of the wave spectrum (Babanin et al., 2017).

Thus the wave-current interactions, along with the topics discussed above and the wave-ice interactions in section below in this article, join the list of the least well performing physics in wave-forecast models. This is largely due to lack of understanding based on observations rather than because of the lack of will to improve the wave forecast in Metocean community. In the meantime, bias in model predictions due to such deficiencies is not negligible, and perhaps somewhat surprisingly is not limited to the specific circumstances of major currents or tidal inlets.

Even such a simple linear effect as refraction-induced convergence and divergence of wave energy have been shown to be important factors in modulating the spatial distribution of wave height on the mesoscale (e.g., Ardhuin et al., 2017). One of the most evident examples of wave refraction is wave trains propagating over mesoscale ocean eddies (**Figure 3**, left panels). Due to the inverted horizontal current shear, one side of the eddy diverges the incoming wave rays, whereas the other side converges the rays (e.g., Mathiesen, 1987). Rapizo et al. (2018) demonstrated that eddy scales as observed from global current reanalysis can potentially create this effect on Southern Ocean swells, but the main impact of these current on the wave-height bias globally is due to another linear effect – change of relative wind speed for the waves on currents (**Figure 3**, right panel).

Therefore, even linear effects due to currents, which are abundant in the Southern Ocean, have global impact on wave climate and bias of wave modeling. Needless to say that the non-linear wave-current exchanges, which for now not accounted for and not even well understood, can potentially have an enormous influence on the waves due to the very large differences between wave and current kinetic energy. This topic requires a dedicated attention of the community through ongoing satellite observations and through the wave buoy network and drifters proposed in this paper (see sections "Wave Evolution at Extreme Fetches," "Severe Extra-Tropical Cyclones at Extreme Fetches," and "Swell Dynamics and Forecasting, With Attention to Arrival Time").

WAVE-ICE INTERACTIONS IN MARGINAL ICE ZONE

Ice edge and the Marginal Ice Zone in the Southern Ocean, unlike in the Arctic, is subject to continuous wave forcing and extreme storms all round the year and hence is an ideal environment for studying wave-ice interactions. Metocean dynamics of the Antarctic Marginal Ice Zone (MIZ) is a topic of great scientific challenge and practical significance. Until recently, the wave forecast models did not predict waves in MIZ (due to lack of knowledge and capability), and in the large-scale models the waves are mostly not taken into account until now.

In terms of knowledge, the wave forecast models have to describe physical mechanisms of wave energy growth, decay, spectrum transformation and wave propagation – in presence of ice. Even if the wind-wave and non-linear energy exchanges are neglected, as the first step, by comparison with dominant energy process of wave decay in ice, such decay by itself accommodates multiple physical mechanisms of wave attenuation, both conservative (wave scattering, reflection and refraction) and dissipative (viscoelastic, turbulent, among others) – see, e.g., Thomson et al. (2018a). Speed of wave-energy propagation also changes in the ice, and provides a family of new dispersion relationships depending on the ice thickness and other mechanical properties (e.g., Collins et al., 2018). The sea ice is a porous material which consists of solid and liquid (brine) phases, with complex elastic, viscous and flexural behaviors as a function of temperature and water salinity – these behaviors define the wave dissipation and propagation and hence need to be known (Wang and Shen, 2010; Mosig et al., 2015, among others). Ultimately, ice is brittle and subject to fatigue under circulating wave forcing, and waves can break the ice (von Bock und Polac, 2016; Williams et al., 2017; Dolatshah et al., 2018). Once this happens, the waves enter a very different dynamic regime: (a) dissipation is driven by floe collisions, rafting, overwash, depends on distribution of floe sizes, and overall appears orders of magnitude weaker (e.g., Bennetts and Williams, 2015; Squire and Montiel, 2016); (b) wave dispersion (shoaling) adjustment

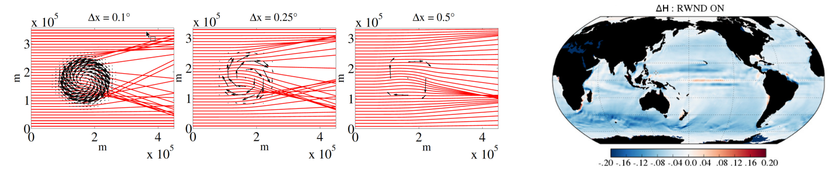

FIGURE 3 | (Left panels) Wave ray refraction on a theoretical eddy. Three different spatial resolutions of the eddy are shown (from left to right): 0.1°, 0.25°, and 0.5°. **(Right panel)** Difference between H_S fields for the simulations with and without currents, if the option of the relative wind speed with respect to the current is activated [Figure is reproduced from Rapizo et al. (2018)].

can change sign (e.g., Peters, 1950), and (c) wind-forced growth becomes (possibly) not negligible (e.g., Rogers et al., 2018). Furthermore, the broken ice can melt (and the wave fetches will increase, promoting the wave growth) or can re-freeze (and ice cover will increase, arresting the wave growth) see, e.g., Liu et al. (2016). The former depends, among other processes, on wave-ocean mixing, and the latter on air-sea heat exchange, hence wave forecast in MIZ becomes essentially an air-sea-wave coupled problem (which is less pronounced across the rest of the world's oceans), see Khon et al. (2014).

Analytical theories for some of the processes outlined above, albeit not all, are available, but quantitative (experimental) guidance is fairly limited: typically, these are case studies rather than non-dimensional parameterisations suitable for global wave modeling in a general case, which conclusion highlights the fact that this kind of measurements are extremely difficult and rare (e.g., Meylan et al., 2014). Thus, advance and even progress in wave forecast is restricted and requires urgent attention, observational in the first place. It should be stressed that the practical problem of wave forecast cannot be approached incrementally – the global wave models are run automatically and require quantitative knowledge of all the above processes, not just some of them or a selection of them, as well as accurate determination of the regime change (ice breakup) – in order to predict waves in MIZ or in the solid ice. For example, if the visco-elastic behavior of ice is known (which it is to some extent), but turbulent dissipation in the water boundary layer below ice is not (which it is not), the wave attenuation cannot be estimated with a reasonable degree of confidence. And if the ice breakup is missed or misplaced by the model, the wave decay, both in time and in space, will be completely off the scale.

In terms of the capability of wave forecast in MIZ, this is not just computing facilities, but mostly operational knowledge on the ice fields which poses predictive limitations. The high-resolution real-time ice information is as essential for modeling wave-ice decay, as good wind fields are for forecasting the wind-wave growth. In this regard, sophisticated analytical theories or precise experimental parameterisations are not helpful if the operational ocean-ice models or satellite observations are not able to provide the relevant properties of ice. Thus, there will always be a gap between research and operational wave modeling, and the practical applications need to balance between exact knowledge and its realistic implementations.

The coupled nature of wave forecast in Antarctica, furthermore, highlights the fact of reciprocal importance of waves for the oceanographic forecast (and, more generally, for air-sea interaction modeling). If waves break the ice and, as a result, it melts faster in spring/summer, this can have significant impact on air-sea fluxes (and not only heat fluxes), even if the ice refreezes in autumn/winter. Note that the first-year ice will be easier to break next summer, and thus the positive feedback loop may accelerate.

Because the presence of waves is more the rule than the exception at the margins of Antarctic ice, this changes the type of ice that forms during the colder months, which can have a profound impact on the heat fluxes and thus the *rate* of ice growth. Specifically, new ice in the presence of waves will tend to be frazil and pancake ice, and will tend to be sheet ice (starting as nilas) in the case without waves. With pancake and frazil ice, liquid water is directly exposed to the cold air, allowing faster freezing (Doble, 2009). With sheet ice, heat must pass through the insulating ice (thus, slower freezing). The ice type also affects the albedo (so heat flux, again) and the surface roughness (and thus drag on the atmosphere).

Thus, wave-ice interactions, along with the Metocean topics above in this article, is a poorly understood type of ocean-wave dynamics, which, correspondingly, leads to poor performance of wave-forecast models in respective conditions. Like the other topics, the main problem in advancing the fundamental understanding and practical modeling of such conditions is lack of observations, and the most suitable environment for such observations is the Southern Ocean. Necessary observations, in addition to wave and flux observations proposed in see Sections "Wave Evolution at Extreme Fetches," "Severe Extra-Tropical Cyclones at Extreme Fetches," and "Swell Dynamics and Forecasting, With Attention to Arrival Time," will require measurements of wave and ice properties within the Marginal Ice Zone. It is suggested to use Antarctic-going ships of opportunity for this purpose.

METOCEAN CLIMATOLOGY IN THE SOUTHERN OCEAN

The Southern Ocean is the least studied ocean area in terms of *in situ* oceanographic and Metocean observations. In the meantime, it demonstrates the fastest growth of winds and waves, both in the mean and in extreme percentiles, by comparison with the other Oceans, at least over the era of satellite remote sensing observations, i.e., since mid 1980s (Young et al., 2011). Seasonally, this most dynamic Metocean region is the only one which demonstrates positive trends for the ocean winds well above mean global values over 2/3rds of the year [except Southern spring, see **Table 1** and Zieger et al. (2014)].

Metocean climate, apart from the winds and currents also includes ice-covered area and ice thickness whose trends in the Southern Ocean are different to the Arctic and in need of dedicated investigations. Overall, Metocean characteristics, particularly their consistent trends at large scales in space in time, indicate regional climate changes, which may be also connected to the global climate behaviors. If subject to vigorous measurements, such characteristics and their trends can serve as climate proxies, potentially more robust by comparison with point characteristics (such as temperature) because the nature of Metocean properties is necessarily an integral over large areas.

Thus, major gaps in the global Metocean climatology come from the Southern Ocean where *in situ* observations, particularly at long-term and systematic basis, are virtually absent. Synergy of the proposed wave and air-sea buoy networks, ice and other Metocean measurements of opportunity (see sections "Wave Evolution at Extreme Fetches," "Severe Extra-Tropical Cyclones at Extreme Fetches," "Swell Dynamics and Forecasting, With Attention to Arrival Time," "Wave-Driven Dispersal of Floating Objects," "Non-linear Wave-Current Interactions," and "Wave-Ice Interactions in Marginal Ice Zone") will help to address this topic of practical and research significance.

MEASUREMENTS IN THE SOUTHERN OCEAN

The paper is proposing a dedicated measurement program for the Southern Ocean, and therefore in this Section we will briefly review available *in situ* observations. Over the last several years, there have been a number of efforts to start Metocean measurements in the Southern Ocean. Most encouraging are attempts of permanent buoy deployments by the Australian Integrated Marine Observing System (Schulz et al., 2012) and by the Ocean Observatories Initiative of the United States National Science Foundation: https://oceanobservatories.org/array/global-southern-ocean/ (see locations in **Figure 4**, top panels). A number of moored and drifting buoys were deployed south of New Zealand by the Metocean Solutions and the Royal New Zealand Navy: http://www.metocean.co.nz/southern-ocean/ (**Figure 4**, bottom left); Metocean observations are conducted by the University of Cape Town in oceanographic voyages of *SA Agulhas II* in the Southern African sector of the South Ocean all the way to Marginal Ice Zone (**Figure 4**, bottom right).

Recently, some investigators have begun using autonomous platforms for Metocean measurements in the Southern Ocean. Thomson and Girton (2017) used a wave glider in the Drake Passage during the austral summer of 2017, with a particular focus on measuring directional wave spectra and wind stress (Thomson et al., 2018b). Schmidt et al. (2017) also use a wave glider to evaluate model winds in the Southern Ocean. These and other mobile platforms continues to operate in 2018–2019. Thus, an expansion of *in situ* wave observations from autonomous surface platforms in addition to traditional moorings, is also likely.

These few deployments, however, while very promising, is literally a drop in the ocean of the most powerful winds and waves. Hundreds of the wind-wave buoys in the Northern Hemisphere, and very few South of equator such as those off the coast of Brazil in the path of Southern swells (Pereira et al., 2017). **Figure 5**[1] highlights the importance

[1] https://protect-au.mimecast.com/s/QcHoCZYMPyCgGNqJizxmHV?domain=jcommops.org

TABLE 1 | Trends in regional average wind speed by calendar month (CNA means Central North Atlantic, SO Southern Ocean, and so on).

	Altimeter trend normalized by 0.203 ms^{-1} decade^{-1}									SSM/I trend normalized by 0.096 ms^{-1} decade^{-1}								
	Atlantic			Indian		Pacific/Southern				Atlantic			Indian		Pacific/Southern			
	NA	CAN	CSA	NIO	CIO	NP	CNP	CSP	SO	NA	CAN	CSA	NIO	CIO	NP	CNP	CSP	SO
Jan	0.0	1.4	1.7*	0.2	1.4*	1.1*	3.0*	1.6*	1.7*	−1.0	2.0	1.5	−0.5	−0.2	2.8*	5.1*	0.2	1.2*
Feb	0.1	0.7	0.6	0.1	0.4	0.1	1.9*	0.8	1.8*	−0.8	1.0	2.1	1.1	−1.3	1.5	4.1*	0.4	0.9
Mar	0.8	1.0*	2.0*	0.5	2.1*	−0.9	1.5*	1.4*	2.0*	2.1	0.3	1.6	1.2	1.3	0.1	2.5*	1.2	0.1
Apr	−0.0	0.9	1.3*	0.9	1.2*	0.3	1.7*	1.5*	1.9*	−1.1*	1.2	0.3	1.3	−0.2	−0.6	1.8	2.1	2.2*
May	0.5	1.5	1.6*	2.2*	0.4	0.0	0.9	0.1	1.6*	0.3	2.4	3.8*	5.4*	−0.3	−0.7	0.4	−0.8	2.1*
Jun	0.4	1.4*	0.8	0.5	1.4*	−0.3	1.8*	1.6*	1.6*	−0.9*	2.9*	1.3	0.0	1.0	−1.2*	2.7*	1.8*	2.8*
Jul	0.3	1.5*	0.4	0.5	1.0*	1.4*	1.3*	1.1*	1.1*	−1.0	1.6*	0.4	−0.9	1.6*	0.4	0.6	0.5	2.6*
Aug	0.5	0.7	3.4*	0.6	1.8*	0.3	1.8	1.6	1.6	−0.5	−1.8*	6.0*	−2.8*	0.8	−4.0*	0.9	−1.1	1.1*
Sep	1.4*	0.6	1.6*	0.8	3.0*	−0.2	1.7*	2.2*	0.5	1.9	0.2	0.1	0.2	2.1	−2.5*	2.8*	1.5	1.8*
Oct	1.5*	1.6*	2.2*	0.4	2.3*	1.9*	1.5*	2.1*	0.1	1.4*	1.1	1.8*	−1.1	0.8	−0.8	0.9	1.8	0.7
Nov	1.4	0.6	1.4*	−1.0	1.6*	0.3	1.7*	1.2*	0.2	0.2	−2.6*	2.3	−4.6*	1.3	0.6	−0.0	1.1	0.6
Dec	−0.3	1.6	0.9	0.1	1.1	2.1*	1.2	0.4	0.7*	−2.0*	0.4	−0.2	−1.0	1.5	3.0	−0.8	0.3	−0.1

*Regional trend estimates are normalized by the global average. Trends which are statistically significant at the 95% level are shown with * and, where both altimeter and SSM/I trends are statistically significant, grids are shaded [**Table 1** is reproduced from Zieger et al. (2014)].*

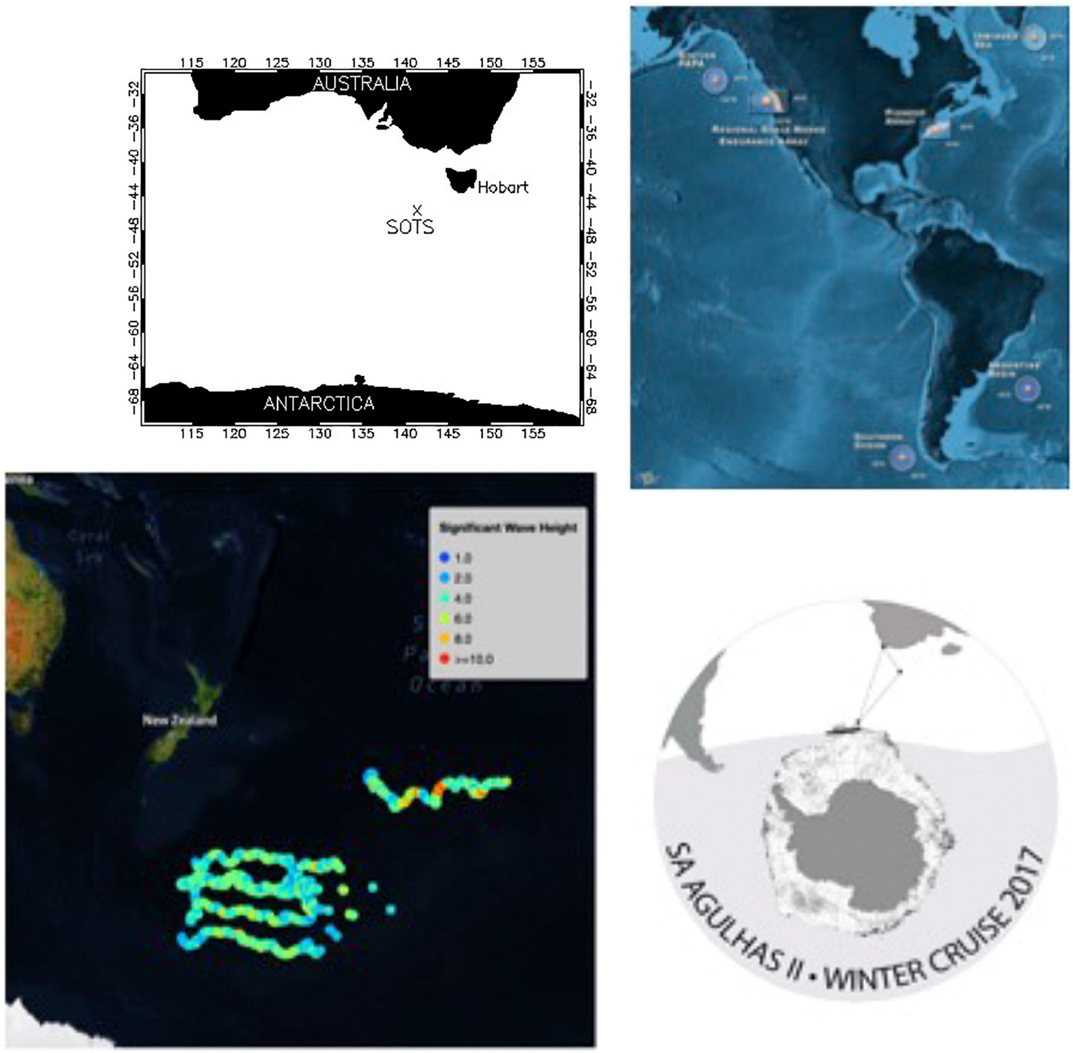

FIGURE 4 | Locations of the Southern Ocean permanent and drifting wave buoys by **(top left)** Australian Bureau of Meteorology, **(top right)** United States NSF Ocean Observatories Initiative, **(bottom left)** Metocean Solutions, New Zealand; **(bottom right)** SA Agulhas II 2017 winter cruise.

of the Metocean observations, and the emptiness of the Southern Ocean where most of the actual problems of the modern Metocean science and applications can and need to be solved (Young et al., 2017). While permanent buoy deployments can be a substantial challenge, drifting buoys, wave gliders and other moving platforms can prove feasible and valuable solution of this challenge for a dedicated international effort.

For an area as geographically remote as the Southern Ocean, remote sensing offers obvious benefits in providing wind and wave data. In terms of wind measurements, there are three potential platforms (radiometers, scatterometers and altimeters). For wave data there are also three options (altimeters, synthetic aperture radar and CFOSat). A number of studies have already looked at global climatology of wind speed and wave height, including the Southern Ocean (Zieger et al., 2009; Vinoth and Young, 2011; Young et al., 2011, 2017; Takbash et al., 2018; Young and Donelan, 2018; Ribal and Young, 2019; Young and Ribal, 2019). These studies, however, are limited to wind speed and significant wave height and suffer from very limited possibilities for Southern Ocean Calibrations.

Our capability to measure directional waves, up to the early 1990s with the launch of ERS-1, was restricted to few areas in the world where buoy data, mainly, was available. Synthetic Aperture Radar (SAR) is the only satellite instrument so far capable to measure the directional spectrum, despite some limitations in its high frequency part. SAR data have been available since then, with a myriad of satellites yielding over 25 years of directional spectra with global coverage. Sentinel-1A and its twin 1B are currently operational, sharing the same orbit plane and therefore with a greater revisit rate. Sentinel-1C is scheduled to be launched in the next 3–4 years, which will increase the temporal sample of the constellation. The recent launch of

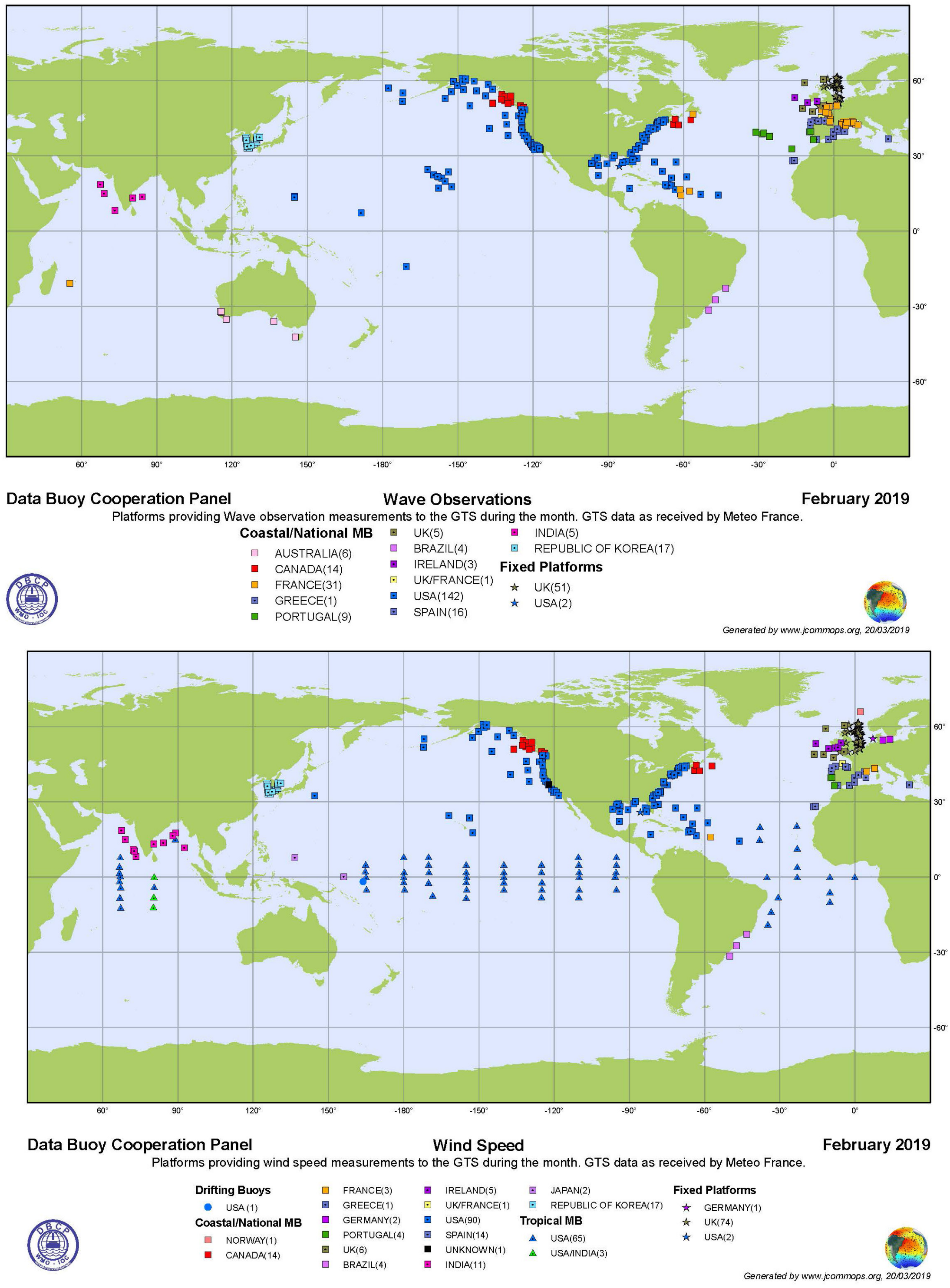

FIGURE 5 | Locations of wave **(top)** and wind **(bottom)** measurements.

CFOSat, which carries a unique scanning wave scatterometer (SWIM) provides the potential to measure the full directional spectrum for components longer than 80 m. This instrument has great potential to open up a new era of wave measurements in environments such as the Southern Ocean. In the context of the proposed network, directional buoy measurements in the scarcely sampled Southern Hemisphere will contribute to the effort to validate such satellite wave observations.

CONCLUSION

Metocean measurements in the Southern Ocean – marine winds and currents, surface waves and swells, ice cover and thickness, among others – are either critically important or, at the very least, can contribute to solving and addressing problems of major significance. Without the Southern Ocean *in situ* observations, it is not possible to resolve the issues of limiting fetches, extreme Extra-Tropical cyclones, swell propagation and attenuation, wave-current interactions. The topics of wave-induced dispersal of floating objects, wave-ice interactions in the Marginal Ice Zone, Metocean climatology and its connection with the global climate cannot be complete in general case without benchmarking the behaviors of these phenomena against observations in this most dynamic area of the global Ocean.

The paper outlines and highlights important gaps in understanding the Metocean processes and suggests a major observational program for this large, but poorly investigated part of the World Ocean. This would include distributed buoy network (drifting and stationary) and autonomous surface vehicles (ASV), intended for measurements of waves and air-sea fluxes in the Southern Ocean.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

REFERENCES

Aguirre, C., Rutllant, J. A., and Falve, M. (2017). Wind waves climatology of the Southeast Pacific Ocean. *Int. J. Climatol.* 37, 4288–4301. doi: 10.1002/joc.5084

Ardhuin, F., Chapron, B., and Collard, F. (2009). Observation of swell dissipation across oceans. *Geophys. Res. Lett.* 36:L06607. doi: 10.1029/2008GL037030

Ardhuin, F., Gille, S. T., Menemenlis, D., Rocha, C. B., Rascle, N., Chapron, B., et al. (2017). Small-scale open ocean currents have large effects on wind wave heights. *J. Geophys. Res.* 122, 4500–4517. doi: 10.1002/2016JC012413

Ardhuin, F., Rogers, E., Babanin, A., Filipot, J.-F., Magne, R., Roland, A., et al. (2010). Semi-empirical dissipation source functions for ocean waves. part I: definitions, calibration and validations. *J. Phys. Oceanogr.* 40, 1917–1941.

Babanin, A. V. (2006). On a wave-induced turbulence and a wave-mixed upper ocean layer. *Geophys. Res. Lett.* 33:L20605. doi: 10.1029/2006GL027308

Babanin, A. V. (2011). *Breaking and Dissipation of Ocean Surface Waves*. Cambridge: Cambridge University Press, 480.

Babanin, A. V. (2018). "Change of regime of air-sea dynamics in extreme Metocean conditions," in *Proceedings of the ASME 2018 37th International Conference on Ocean, Offshore and Arctic Engineering OMAE2018*, Madrid.

Babanin, A. V., Hwung, H.-H., Shugan, I., Roland, A., van der Westhuysen, A., Chawla, A., et al. (2011). "Nonlinear waves on collinear currents with horizontal velocity gradient," in *Proceedings of the 12th International Workshop on Wave Hindcasting and Forecasting and 3rd Coastal Hazards Symposium*, Big Island.

Babanin, A. V., and Jiang, H. (2017). "Ocean swell, how much do we know," in *Proceedings of the ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering OMAE2017*, Trondheim.

Babanin, A. V., van der Westhuysen, A., Chalikov, D., and Rogers, W. E. (2017). Advanced wave modelling including wave-current interaction. *J. Mar. Res.* 75, 239–262.

Babanin, A. V., and Waseda, T. (2015). "Diffraction and instability of short-crested limited-length one-dimensional coherent wave trains," in *Proceedings of the ASME 2015 34th International Conference on Ocean, Offshore and Arctic Engineering OMAE2015*, St John's, NL.

Badulin, S. I., Babanin, A. V., Zakharov, V. E., and Resio, D. (2007). Weakly turbulent laws of wind-wave growth. *J. Fluid Mech.* 591, 339–378.

Balk, A. M. (2001). Anomalous diffusion of a tracer advected by wave turbulence. *Phys. Lett. A* 279, 370–378.

Batchelor, G. K., and Townsend, A. A. (1956). "Turbulent diffusion," in *Surveys in Mechanics*, eds G. K. Batchelor and H. Bondi (Cambridge: Cambridge University Press), 352–399.

Bennetts, L. G., and Williams, T. D. (2015). Water wave transmission by an array of floating discs. *Proc. R. Soc. A* 471:20140698. doi: 10.1098/rspa.2014.0698

Cavaleri, L., Alves, J.-H. G. M., Ardhuin, F., Babanin, A., Banner, M., Belibassakis, K., et al. (2007). Wave modelling – the state of the art. *Progr. Oceanogr.* 75, 603–674.

Collins, C., Doble, M., Lund, B., and Smith, M. (2018). Observations of surface wave dispersion in the marginal ice zone. *J. Geophys. Res. Oceans* 123, 3336–3354. doi: 10.1029/2018JC013788

Doble, M. J. (2009). Simulating pancake and frazil ice growth in the Weddell Sea: a process model from freezing to consolidation. *J. Geophys. Res.* 114:C09003. doi: 10.1029/2008JC004935

Dolatshah, A., Nelli, F., Bennetts, L. G., Alberello, A., Meylan, M. H., Monty, J. P., et al. (2018). Hydroelastic interactions between water waves and floating freshwater ice. *Phys. Fluids* 30:091702.

Donelan, M. A. (1999). "Wind-induced growth and attenuation of laboratory waves," in *Wind-Over-Wave Couplings. Perspective and Prospects*, eds S. Sajadi, N. H. Thomas, and J. C. R. Hunt (Oxford: Clarendon Press), 183–194.

Donelan, M. A., Curcic, M., Chen, S. S., and Magnusson, A. K. (2012). Modeling waves and wind stress. *J. Geophys. Res.* 117:C00J23.

Falkovich, G. (2009). Could waves mix the ocean? *J. Fluid Mech.* 638, 1–4. doi: 10.1017/S0022112009991984

Gordon, J. P. (1986). Theory of the soliton self-frequency shift. *Opt. Lett.* 11, 662–664.

Herterich, K., and Hasselmann, K. (1982). The horizontal diffusion of tracers by surface waves. *J. Phys. Oceanogr.* 12, 704–712.

Iwano, K., Takagaki, N., Kurose, R., and Komori, S. (2013). Mass transfer velocity across the breaking air-water interface at extremely high wind speeds. *Tellus B* 65:21341. doi: 10.3402/tellusb.v65i0.21341

Jiang, H., Babanin, A. V., and Chen, G. (2016). Event-based validation of swell arrival time. *J. Phys. Oceanogr.* 46, 3563–3569.

Khon, V. C., Mokhov, I. I., Pogarskiy, F. A., Babanin, A. V., Dethloff, K., Rinke, A., et al. (2014). Wave heights in the 21st century Arctic Ocean simulated with a regional climate model. *Geophys. Res. Lett.* 41, 2956–2961. doi: 10.1002/2014GL059847

Leikin, I. A., Donelan, M. A., Mellen, R. H., and McLaughlin, D. J. (1995). Asymmetry of wind generated waves studied in a laboratory tank. *Nonlin. Process. Geophys.* 2, 280–289.

Liu, Q., Babanin, A. V., Zieger, S., Young, I. R., and Guan, C. (2016). Wind and wave climate in the Arctic Ocean as observed by altimeters. *J. Clim.* 29, 7957–7975.

Mathiesen, M. (1987). Wave refraction by a current whirl. *J. Geophys. Res.* 92, 3905–3912. doi: 10.1029/JC092iC04p03905

McNeil, C., and D'Asaro, E. (2007). Parameterization of air-sea gas fluxes at extreme wind speeds. *J. Mar. Sys.* 66, 110–121.

Meucci, A., Young, I. R., and Breivik, O. (2018). Wind and wave extremes from atmosphere and wave model ensembles. *J. Clim.* 31, 8819–8843. doi: 10.1175/JCLI-D-18-0217.1

Meylan, M., Bennetts, L. G., and Kohout, A. (2014). In situ measurements and analysis of ocean waves in the Antarctic marginal ice zone. *Geophys. Res. Lett.* 41, 5046–5051. doi: 10.1002/2014GL060809

Mosig, J. E. M., Montiel, F., and Squire, V. A. (2015). Comparison of viscoelastic-type models for ocean wave attenuation in ice-covered seas. *J. Geophys. Res. Oceans* 120, 6072–6090.

Pereira, H. P. P., Violante-Carvalho, N., Nogueira, I. C. M., Babanin, A. V., Liu, Q., de Pinho, U., et al. (2017). Wave observations from an array of directional buoys over the Southern Brazilian Coast. *Ocean Dyn.* 67, 1577–1591. doi: 10.1007/s10236-017-1113-9

Peters, A. S. (1950). The effect of a floating mat on water waves. *Commun. Pure Appl. Math*. 3, 319–354.

Pierson, W. J. Jr., and Moskowitz, L. (1964). A proposed spectral form for fully developed wind seas based on the similarity theory of S.A. Kitaigorodskii. *J. Geophys. Res*. 69, 5181–5190.

Portilla-Yandún, J. (2018). The global signature of Ocean wave spectra. *Geophys. Res. Lett*. 45, 267–276. doi: 10.1002/2017GL076431

Powell, M. D., Vickery, P. J., and Reinhold, T. A. (2003). Reduced drag coefficient for high wind speeds in tropical cyclones. *Nature* 422, 279–283.

Rapizo, H., Babanin, A. V., Schulz, E., Hemer, M. A., and Durrant, T. H. (2015). Observation of wind-waves from a floating buoy in the Southern Ocean. *Ocean Dyn.* 75, 1275–1288. doi: 10.1007/s10236-015-0873-3

Rapizo, H., Durrant, T., and Babanin, A. V. (2018). An assessment of the impact of surface currents on wave modeling in the Southern Ocean. *Ocean Dyn.* 67, 1577–1591. doi: 10.1007/s10236-018-1171-7

Ribal, A., and Young, I. R. (2019). 33 years of globally calibrated wave height and wind speed data based on altimeter observations. *Sci. Data* 6:77. doi: 10.1038/s41597-019-0083-9

Rogers, W. E. (2002). *The U.S. Navy's Global Wind-Wave Models: An Investigation into Sources of Errors in Low-Frequency Energy Predictions*. Washington, DC: NRL.

Rogers, W. E., Posey, P., Li, L., and Allard, R. (2018). *Forecasting and Hindcasting Waves In and Near the Marginal Ice Zone: Wave Modeling and the ONR "Sea State" Field Experiment*. Washington, DC: Naval Research Laboratory.

Schmidt, K., Swart, S., Reason, C., and Nicholson, S. (2017). Evaluation of satellite and reanalysis wind products with in situ Wave Glider wind observations in the Southern Ocean. *J. Ocean Atm. Tech*. 34, 2551–2568. doi: 10.1175/JTECH-D-17-0079.1

Schulz, E., Josey, S. A., and Verein, R. (2012). First air-sea flux mooring measurements in the southern ocean. *Geophys. Res. Lett.* 39:L16606. doi: 10.1029/2012GL052290

Segur, H., Henderson, D., Carter, J., Hammack, J., Li, C.-M., Pheiff, D., et al. (2005). Stabilizing the benjamin-feir instability. *J. Fluid Mech.* 539, 229–271.

Semedo, A., Suselj, K., Rutgersson, A., and Sterl, A. (2011). A Global View on the Wind Sea and Swell Climate and Variability from ERA-40. *J. Clim.* 24, 1461–1479.

Shrira, V. I., and Slunyaev, A. V. (2014). Nonlinear dynamics of trapped waves on jet currents and rogue waves. *Phys. Rev. E* 89:041002.

Snodgrass, F. E., Groves, G. W., Hasselmann, K., Miller, G. R., Munk, W. H., Powers, W. H., et al. (1966). Propagation of ocean swell across the Pacific. *Philos. Trans. R. Soc. Lond. A* 249, 431–497.

Soomere, T., Viidebaum, M., and Kalda, J. (2011). On dispersion properties of surface motions in the Gulf of Finland. *Proc. Eston. Acad. Sci.* 60, 269–279.

Squire, V., and Montiel, F. (2016). Evolution of directional wave spectra in the marginal ice zone: a new model tested with legacy data. *J. Phys. Oceanogr*. 46, 3121–3137.

Takbash, A., Young, I. R., and Breivik, O. (2018). Global wind speed and wave height extremes derived from satellite records. *J. Clim.* 32, 109–126. doi: 10.1175/JCLI-D-18-0520.1

Thomson, J., Ackley, S., Girard-Ardhuin, F., Ardhuin, F., Babanin, A. V., Boutin, G., et al. (2018a). Overview of the Arctic Sea State and Boundary layer physics program. *J. Geophys. Res.* 123, 8674–8687. doi: 10.1002/2018JC013766

Thomson, J., Girton, J., Jha, R., and Trapani, A. (2018b). Measurements of directional wave spectra and wind stress from a wave glider autonomous surface vehicle. *J. Atmos. Ocean Tech.* 35, 347–363.

Thomson, J., and Girton, J. (2017). Sustained measurements of Southern Ocean air-sea coupling from a wave glider autonomous surface vehicle. *Oceanogr. Magaz.* 30, 104–109.

Thomson, J., and Rogers, W. E. (2014). Swell and sea in the emerging Arctic Ocean. *Geophys. Res. Lett.* 41, 3136–3140.

Tolman, H. L. (2002). *User Manual and System Documentation of WAVEWATCH-III Version 2.22 Technical Note*. Silver Spring: NOAA.

Vinoth, J., and Young, I. R. (2011). Global estimates of extreme wind speed and wave height. *J. Clim.* 24, 1647–1665. doi: 10.1175/2010JCLI3680.1

von Bock und Polac, R. U. F. (2016). *The Mechanical Behavior of Model-Scale Ice: Experiments, Numerical Modeling and Scalability*. Helsinki: Aalto University publication. *Doctoral Dissertation*.

Wang, R., and Shen, H. H. (2010). Gravity waves propagating into an ice-covered ocean: a viscoelastic model. *J. Geophys. Res. Oceans* 115, 1–12.

Wavewatch III® Development Group (2016). *User Manual and System Documentation of WAVEWATCH III® Version 5.16. Tech. Note 329*. College Park, MD: NOAA.

Williams, T. D., Rampal, P., and Bouillon, S. (2017). Wave–ice interactions in the neXtSIM sea-ice model. *Cryosphere* 11, 2117–2135. doi: 10.5194/tc-11-2117-2017

Young, I. R. (2006). Directional spectra of hurricane wind waves. *J. Geophys. Res.* 111, 1–14.

Young, I. R., Babanin, A. V., and Zieger, S. (2013). The decay rate of ocean swell observed by altimeter. *J. Phys. Oceanogr.* 43, 2322–2333.

Young, I. R., and Donelan, M. A. (2018). On the determination of global ocean wind and wave climate from satellite observations. *Remote Sens. Environ.* 215, 228–241. doi: 10.1016/j.rse.2018.06.006

Young, I. R., and Ribal, A. (2019). Multi-platform evaluation of global trends in wind speed and wave height. *Science* 364, 548–552. doi: 10.1126/science.aav9527

Young, I. R., Sanina, E., and Babanin, A. V. (2017). Calibration and cross-validation of a global wind and wave database of altimeter, radiometer and scatterometer measurements. *J. Atmos. Ocean. Technol.* 34, 1285–1306. doi: 10.1175/JTECH-D-16-0145

Young, I. R., Zieger, S., and Babanin, A. V. (2011). Global trends in wind speed and wave height. *Science* 332, 451–455. doi: 10.1126/science.1197219

Zakharov, V. E., and Zaslavskii, M. M. (1982). Kinetic equation and Kolmogorov's spectra in a week turbulence theory of wind waves. Izv. Akad. Nauk SSSR, Fiz. *Atmos. Okeana* 18, 970–979.

Zieger, S., Babanin, A. V., and Young, I. R. (2014). Changes in ocean surface winds with a focus on trends of regional and monthly mean values. *Deep Sea Res. Part 1* 86, 56–67.

Zieger, S., Vinoth, J., and Young, I. R. (2009). Joint calibration of multi-platform altimeter measurements of wind speed and wave height over the past 20 years. *J. Atmos. Ocean. Tech.* 26, 2549–2564. doi: 10.1175/2009JTECHA1303.1

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The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Marine Science

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Toward a Coordinated Global Observing System for Seagrasses and Marine Macroalgae

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In coastal waters around the world, the dominant primary producers are benthic macrophytes, including seagrasses and macroalgae, that provide habitat structure and food for diverse and abundant biological communities and drive ecosystem processes. Seagrass meadows and macroalgal forests play key roles for coastal societies, contributing to fishery yields, storm protection, biogeochemical cycling and storage, and important cultural values. These socio-economically valuable services are threatened worldwide by human activities, with substantial areas of seagrass and macroalgal forests lost over the last half-century. Tracking the status and trends in marine macrophyte cover and quality is an emerging priority for ocean and coastal management, but doing so has been challenged by limited coordination across the numerous efforts to monitor macrophytes, which vary widely in goals, methodologies, scales, capacity, governance approaches, and data availability. Here, we present a consensus assessment and recommendations on the current state of and opportunities for advancing global marine macrophyte observations, integrating contributions from a community of researchers with broad geographic and disciplinary expertise. With the increasing scale of human impacts, the time is ripe to harmonize marine macrophyte observations by building on existing networks and identifying a core set of common metrics and approaches in sampling design, field measurements, governance, capacity building, and data management. We recommend a tiered observation system, with improvement of remote sensing and remote underwater imaging to expand capacity to capture broad-scale extent at intervals of several years, coordinated with stratified *in situ* sampling annually to characterize the key variables of cover and taxonomic or functional group composition, and to provide ground-truth. A robust networked system of macrophyte observations will be facilitated by establishing best practices, including standard protocols, documentation, and sharing of resources at all stages of workflow, and secure archiving of open-access data. Because such a network is necessarily distributed, sustaining it depends on close engagement of local stakeholders and focusing on building and long-term maintenance of local capacity, particularly in the developing world. Realizing these recommendations will produce more effective, efficient, and responsive observing, a more accurate global picture of change in vegetated coastal systems, and stronger international capacity for sustaining observations.

Keywords: biodiversity, seagrass, network, macroalgae, biodiversity observation network (BON), essential ocean variables (EOV)

INTRODUCTION

Seagrasses and macroalgae (macrophytes) are the foundation of submerged vegetated ecosystems in shallow coastal waters throughout the world. They are among the most productive habitats on land or sea, provide critical habitat for a diverse range of animals, including commercial, and subsistence fisheries and species of concern (Heck et al., 2003; Hamilton and Konar, 2007; Hughes et al., 2009; Unsworth R. et al., 2018; Lefcheck et al., 2019), and provide coastal protection, uptake of terrestrial nutrient runoff, and carbon storage. These habitats and the services they provide are threatened by a range of interacting human activities, notably coastal development, declining water quality, invasive species, climate warming, sea level rise, and storms (Carpenter et al., 2008; Waycott et al., 2009; Polidoro et al., 2010; Filbee-Dexter and Wernberg, 2018). Large, perennial organisms such as seagrasses and canopy-forming macroalgae (Laminariales, Tilopteridales, Desmarestiales, and Fucales, commonly known as kelp and fucoids or rockweeds) are especially vulnerable to human disturbance and, under repeated and interacting impacts, they often yield dominance to faster-growing opportunistic algae (Duarte, 1995; Bonsdorff et al., 1997; Filbee-Dexter and Wernberg, 2018). Growing understanding of the valuable services provided by seagrass and macroalgal stands has strengthened interest in conserving them. Originally, these concerns were based primarily on contributions of coastal vegetated ecosystems to commercial fisheries but have expanded to include their importance to biodiversity and threatened species, artisanal fisheries (Nordlund et al., 2018), good water quality, resilience against climate change, and cultural significance (Macreadie et al., 2017; Wernberg et al., 2019).

As a result of their ecological value and vulnerability, protection of coastal macrophyte habitats is mandated by many national and international conventions and policies, including the international Ramsar Convention on Wetlands of International Importance and Convention on Biological Diversity (Miloslavich et al., 2018) as well as the USEPA 2003 Clean Water Act, the European Union 1992 Habitat Directive, the 2000 Water Framework Directive, and the 2008 Marine Strategy Framework Directive. Effective resource management requires understanding the extent, conditions, and trends in the marine ecosystems that support them. Moreover, because drivers of change interact, ecosystem-level responses to environmental forcing can be complex, emphasizing the need for tracking both environmental conditions and key biological components of these systems (Duffy et al., 2013a). For example, long-term field monitoring and experiments in the Baltic Sea suggest that seagrass decline resulted from combined nutrient loading and the cascading effects of fishing (Baden et al., 2010; Eriksson et al., 2011; Östman et al., 2016). The interdependency of coastal habitat quality and offshore fisheries in this region would not have been recognized without long-term monitoring. Such interactions also highlight the importance of connecting monitoring to ecological theory, experiments, and modeling to evaluate mechanisms and the generality of system dynamics (Duffy et al., 2013b). For example, both shallow rooted macrophytes (Short and Burdick, 1996; Greening et al., 2018) and macroalgal forests (Benedetti-Cecchi et al., 2015; Filbee-Dexter and Wernberg, 2018) can shift rapidly to unvegetated or alternate vegetation states, with important management implications. Experiments and theory help predict the warning signs and mechanisms of such transitions. Knowledge derived from both monitoring macrophytes and mechanistic research is critical to informing policy and helping to design and implement effective management actions. Similarly, macrophyte species differ widely in morphology, but these traits often covary predictably with physiology (Duarte, 1991). Forecasting the responses of macrophyte communities to perturbations can be strengthened by incorporating mechanistic trait-based approaches, as has proven successful in terrestrial plants (Wright et al., 2004) and corals (Darling et al., 2012; Madin et al., 2014).

More than 45 programs worldwide conduct repeated observations of submerged vegetation at regional to global scales (**Table S1**), providing key indicators of marine ecosystem change (Marbà et al., 2013; Krumhansl et al., 2016; Miloslavich et al., 2018). Most programs operate in isolation and are restricted in space and duration (Krumhansl et al., 2016). This constrains our perception of status, trends, and dynamics of macrophyte ecosystems on the scales necessary for informing effective management and policy, particularly on national and international scales. The Global Ocean Observing System (GOOS), launched in 2009, oversaw a community process to identify a set of core physical, biogeochemical, and more recently biological "Essential Ocean Variables" (EOVs), aimed at providing data to inform requirements for international reporting and assessments (Lindstrom et al., 2012). Seagrass and macroalgal canopy cover and composition were identified as two of the seven biological EOVs based on their scientific and societal relevance and feasibility for global implementation (Miloslavich et al., 2018). However, coordinated observations of these coastal macrophytes have lagged behind those of pelagic phytoplankton and coral reefs. GOOS is collaborating with the Partnership for the Observation of the Global Ocean (POGO), the Marine Biodiversity Observation Network (MBON) (Muller-Karger et al., 2018), and other parties to draft plans for long-term, large-scale implementation of the EOVs. The immediate goal is recommendations for consolidating existing data and metadata toward a globally coherent system under the FAIR (findable, accessible, interoperable, and reusable) data principle (Wilkinson et al., 2016).

This white paper presents a consensus assessment and recommendations for advancing observation of marine macrophytes, integrating contributions from researchers with broad geographic and disciplinary expertise. We carried out an in-depth analysis of the current knowledge of seagrass and macroalgae monitoring efforts worldwide. Based on this review, we summarize the status of marine macrophyte habitats, focusing on seagrasses, macroalgal forests, and pelagic *Sargassum*; the services they provide to humanity; and the threats facing them. We then outline the rationale for considering macrophyte abundance and composition as Essential Ocean Variables as well as steps toward more effectively incorporating them into global observing systems that inform policy and management needs. We close with recommendations for establishing a coordinated global observing system for marine macrophytes.

VEGETATION TYPES

Seagrasses

Seagrasses are a group of 72 species of flowering plants that spend all or most of their lives submerged in seawater (Short et al., 2011). Most seagrasses root in shallow sediment bottoms (exceptions include the rocky shore surfgrasses, *Phyllospadix* spp., as well genera like *Amphibolis, Thalassodendron, Cymodocea*, and *Posidonia*, which occur on rocky bottoms under some conditions). Seagrass depth limits are set by sufficient light to support net positive growth—generally <20 m depth, but deeper in oceanic waters (e.g., >30 m in the Canary Islands) and much shallower in turbid estuaries. Seagrasses form dense populations in estuarine and protected coastal waters from the equator to high latitudes on all continents except Antarctica, and are most diverse in southeast Asia and Western Australia (Lamit et al., 2017). Six seagrass bioregions have been recognized (**Figure 1**), encompassing all the oceans of the world, across both tropical and temperate waters (Short et al., 2007). The seagrass Atlas (Green and Short, 2003) was able to identify and confirm only around 150,000 km^2 of seagrass meadows globally. But the global area of habitat suitable for seagrasses has recently been estimated at around 1.6 million km^2 based on environmental models (Jayathilake and Costello, 2018), and the total coastal area with sufficient light for seagrass growth is estimated at 4.32 million km^2 (Gattuso et al., 2006; Duarte, 2017), not taking into

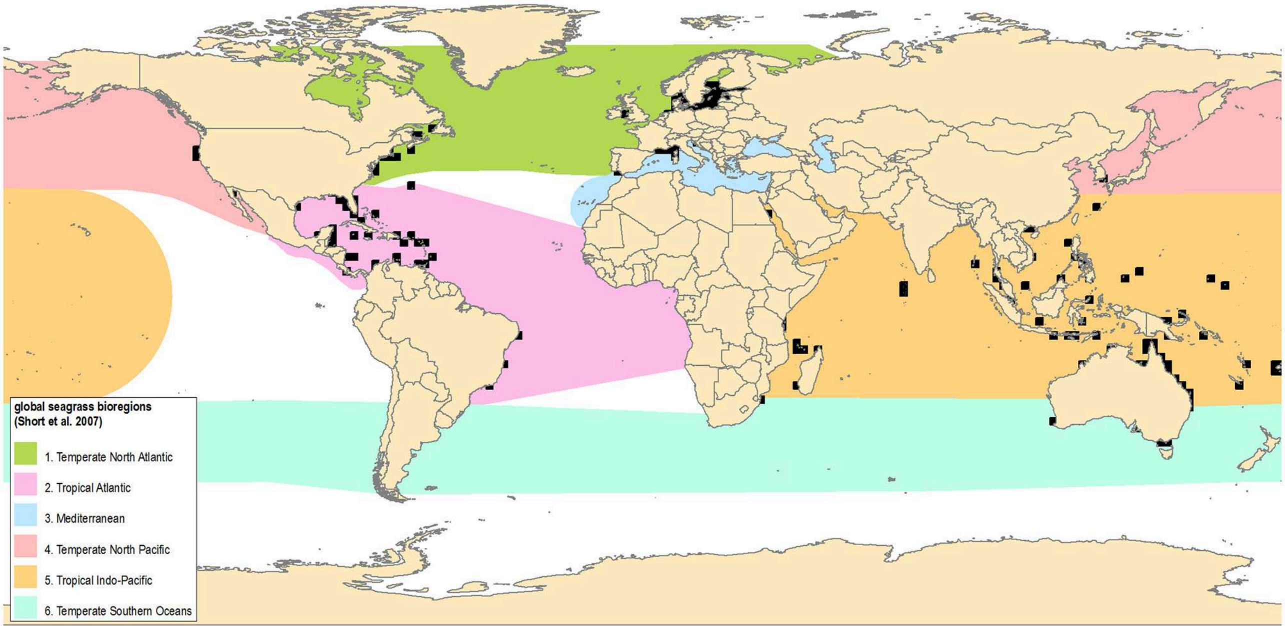

FIGURE 1 | Locations of current long-term seagrass observing networks and seagrass geographic bioregions. (1) Temperate North Atlantic, (2) Tropical Atlantic, (3) Mediterranean, (4) Temperate North Pacific, (5) Tropical Indo-Pacific, (6) Temperate Southern Oceans. Observing systems are shown as 2 degree grids.

account other habitat requirements such as suitable substrate conditions. Modeled estimates of seagrass potential extent can cover much larger areas than *in situ* measurements but have high uncertainty, particularly on local scales, as they are based on environmental conditions considered suitable rather than on direct evidence of seagrass presence.

Seagrasses support biotic communities that are often considerably more diverse and productive than in surrounding unvegetated sediments as a result of the physical structure of seagrass meadows and the high productivity of associated algae (Orth and Van Montfrans, 1984; Duffy et al., 2013b). Seagrass meadows are especially important as nursery habitats for juvenile life stages of fishes and larger invertebrates (Beck et al., 2001; Heck et al., 2003; Lefcheck et al., 2019) and provide feeding and breeding habitats for several threatened species, including sea turtles and sirenians (dugongs and manatees). However, much seagrass production is ungrazed and flows into detritus food webs or is buried in sediments, making seagrass meadows important sites of blue carbon burial (Fourqurean et al., 2012; Duarte et al., 2013). Exported seagrass material may also contribute to carbon sequestration in deeper oceanic sinks distant from seagrass habitats (Duarte and Krause-Jensen, 2017).

A host of global and local stressors affect seagrasses, including sediment and nutrient runoff, physical disturbance, algal blooms, invasive species, climate warming, and disease (Orth et al., 2006; Waycott et al., 2009). The sheltered coastal and island waters in which seagrasses grow best are prime real estate for coastal and harbor development, imposing pressures from land reclamation, deforestation, aquaculture, fishing, and marine debris (Unsworth R. et al., 2018). A principal local stressor throughout the world is poor water quality resulting from nutrient pollution (eutrophication) and/or sediment loading from land runoff (Cloern, 2001; Burkholder et al., 2007). Requirements for clear water and low nutrient concentrations make seagrasses vulnerable to eutrophication, as nutrient and sediment loading reduce light availability and favor faster-growing algae (Burkholder et al., 2007). Recently, massive influxes of pelagic *Sargassum* spp. have caused loss of near-coastal seagrass meadows in the Caribbean (van Tussenbroek et al., 2017), and invasive macroalgae can threaten both seagrasses and canopy macroalgae elsewhere as well (e.g., *Lophocladia lallemandii* in the Mediterranean Sea, Ballesteros et al., 2007a). Disruption of coastal food webs can also threaten seagrass ecosystems, both by altering grazing by megaherbivores and through cascading effects of overfishing (Eriksson et al., 2011) and hunting (Hughes et al., 2013). Climate change is a growing concern for seagrass ecosystems (Waycott et al., 2011; Short et al., 2016; Fortes et al., 2018). Many temperate seagrasses are sensitive to high temperatures, and warming-induced mortality has been observed over recent decades in several regions (Short and Neckles, 1999; Reusch et al., 2005; Moore and Jarvis, 2008; Hammer et al., 2018). While warming can be particularly detrimental near the equatorial end of the distribution range (e.g., major declines of *Zostera marina* at its southern range in SW Iberia; Cunha et al., 2013), seagrasses and macroalgae may instead benefit from warming at the polar end of the distribution range (Mieszkowska et al., 2006, 2014; Kortsch et al., 2012; Krause-Jensen et al., 2012). Shallow seagrasses are also vulnerable to die-off under hypersaline conditions ($>$ 45 psu) resulting from combined low precipitation and elevated water temperatures (Walker and McComb, 1990; Koch et al., 2007; Johnson et al., 2018). Large-scale ($>$ 50 km^2) seagrass die-off associated with hypersaline conditions is a recurring problem in Florida Bay in the USA, in the French Mediterranean Sea, and southern Australia (Robblee et al., 1991; Seddon et al., 2000; Greve et al., 2003), and is expected to become more frequent and widespread under future warming. Another serious concern is the frequency of disease epidemics, which are associated with warming in many systems (Harvell et al., 2002; Altizer et al., 2013; Kaldy, 2014; Sullivan et al., 2017).

In part as a result of these multifarious stressors, ten of the 72 currently known seagrass species are at elevated risk of extinction and three species are classified as Endangered (Short et al., 2011). In the Caribbean Sea, the CARICOMP regional monitoring study detected long-term declines in the relative abundance of the robust, slow-growing seagrass *Thalassia testudinum* in 43% of 35 long-term monitoring stations consistent with environmental deterioration (van Tussenbroek et al., 2014). In the Mediterranean, dramatic losses in cover of the seagrasses *Posidonia* and *Cymodocea* have been predicted (Chefaoui et al., 2018) and observed, and many local extinctions were reported in SW Iberia (Cunha et al., 2013). Many tropical Pacific seagrasses are also declining, mainly in populated areas, due to increased nutrient loading and sedimentation, the two most common stressors of seagrasses worldwide (Short et al., 2014). It is likely that ongoing environmental change will similarly lead to seagrass declines in other locations including the diverse tropical regions where robust environmental protection is often poorly implemented. The wide uncertainty in estimates of global seagrass area, and particularly the geographic bias in our knowledge, makes estimates of threats and projected losses speculative, but there is widespread concern about losing seagrass meadows that have not yet been identified or assessed. This makes establishing a globally harmonized approach for monitoring these coastal ecosystems all the more important and urgent.

Benthic Macroalgal Forests

A variety of large macroalgae live in dense populations that can be described as marine forests (Wernberg and Filbee-Dexter, 2019). Among the most prominent and widely distributed are large brown algae (Ochrophyta) known as kelps and rockweeds (orders Laminariales, Tilopteridales, Desmarestiales, and Fucales), the largest being the giant kelp *Macrocystis pyrifera*, which can reach >45 m in length. Large green (Chlorophyta) and red (Rhodophyta) macroalgae can also form marine forests. Macroalgal forests vary greatly in height, structure, and function and, like seagrasses, provide three-dimensional landscape structure that generally supports dense communities of other algae, invertebrates, fishes, and some marine mammals—most of which could not persist in the absence of the canopy (Tegner and Dayton, 2000; Krumhansl and Scheibling, 2012; Teagle et al., 2017).

Macroalgal forests are confined to hard substrata, typically rocky reefs, and are generally found from the intertidal zone to 15–25 meters in depth, although the lower limit can exceed 50–100 m in clear water (Graham et al., 2007; Marzinelli et al., 2015b; Assis et al., 2016, 2018). Tidal height, water clarity, wave exposure, and herbivory, particularly by sea urchins, often limit their spatial distribution. Macroalgal forests are particularly prominent along temperate and polar latitudes (Steneck and Johnson, 2013; Wernberg et al., 2019), but laminarian kelp forests occur near the equator in clear, nutrient-rich water below the thermocline (>30 meters) (Graham et al., 2007), and extensive *Sargassum* forests are common in many shallow tropical and subtropical environments (Fulton et al., 2014). Macroalgal forests dominate at least 25% of the world's coastlines (Steneck and Johnson, 2013; Wernberg et al., 2019).

Macroalgal forests are impacted by a variety of stressors, including sediment and nutrient loading (Foster and Schiel, 2010); direct harvesting (Vásquez et al., 2014); fishing (Ling et al., 2009); climate change in the form of rising water temperatures, ocean acidification, extreme weather events, melting glaciers (Mieszkowska et al., 2006; Wernberg et al., 2012; Araujo et al., 2016); pollution by heavy metals and organic chemicals (Thibaut et al., 2005; Coleman et al., 2008; Fowles et al., 2018); harvesting for food and the phycocolloid industry (Rebours et al., 2014; Buschmann et al., 2017); aquaculture (Yang et al., 2015); and disease (Altizer et al., 2013; Marzinelli et al., 2015a). Climate warming has directly affected the abundance, distribution, and geographic range of many macroalgal species (Johnson et al., 2011; Nicastro et al., 2013; Assis et al., 2014; Brodie et al., 2014; Neiva et al., 2015; Filbee-Dexter et al., 2016; Lourenco et al., 2016; Wernberg et al., 2016; Martinez et al., 2018). Near the poles, climate warming is likely to stimulate the expansion of macroalgal forests (Krause-Jensen and Duarte, 2014). Disturbances to food webs have also threatened macroalgal forests. Overfishing has led indirectly to loss of canopy-forming macroalgae by releasing sea urchins from predatory control and allowing them to overgraze kelps (Wilmers et al., 2012; Filbee-Dexter and Scheibling, 2014; Konar et al., 2014; Ling et al., 2015; Estes et al., 2016). Such trophic cascades are expected to increase in the future. Other herbivores can similarly overgraze macroalgal forests (Chenelot and Konar, 2007; Gianni et al., 2017). Over the last decade or so, tropical herbivores have expanded into temperate regions, increasing the abundance, diversity, and feeding pressure of herbivores and in some cases eradicating macroalgal forests (Johnson et al., 2013; Vergés et al., 2014; Araujo et al., 2016).

As a result of these multiple stressors, macroalgal communities are declining worldwide, particularly laminarian kelp forests. Among macroalgal time series extending >20 years, 61% are in decline and only 5% are increasing (Krumhansl et al., 2016; Wernberg et al., 2019). Losses of canopy-forming macroalgae are predicted to increase with rising global temperatures and more frequent and severe weather events (Oliver et al., 2018). Unfortunately, 66% of the bioregions with laminarian kelp forests have no time series data (Mieszkowska et al., 2006; Krumhansl et al., 2016). In many regions, kelps and other canopy-forming macroalgae have been in transition to dominance by turf and coralline algae over the past two decades (Benedetti-Cecchi et al., 2001; Filbee-Dexter and Scheibling, 2014; Strain et al., 2014; Filbee-Dexter and Wernberg, 2018). Community states dominated by turf or coralline algae are often maintained by multiple, complex feedbacks, suppressing their return to dominance by canopy-forming macroalgae (Benedetti-Cecchi et al., 2015; O'Brien et al., 2015; Rindi et al., 2017; Filbee-Dexter and Wernberg, 2018). This emphasizes the need to understand ecological processes as well as abundance trends.

Pelagic Macroalgae

Large macroalgae also occur in the open pelagic regions of the Atlantic Ocean, Gulf of Mexico, and Caribbean Sea, where extensive accumulations of two pelagic brown seaweeds, *Sargassum fluitans* and *S. natans*, occur with a diversity of morphological forms (Schell et al., 2015). Both species are holopelagic, reproduce by vegetative fragmentation (Huffard et al., 2014) and form "Lagrangian ecosystems" that drift with winds and currents. In addition to these naturally pelagic macroalgae, floating rafts of normally benthic algae have increased over recent years in several regions. In the East China Sea, floating seaweed rafts are formed by *S. horneri*, which grows on the bottom but can be detached by strong waves (Qi et al., 2017). Aggregations of detached *S. horneri* have recurred since 2008, along with blooms of the green macroalga *Ulva prolifera* in the Yellow Sea. Strategies have been developed to monitor these algal blooms that can also be applied to *Sargassum* blooms (Hu et al., 2017). Kelps can also separate from the substrate and drift long distances, transporting biomass and associated animals on their way through the ocean (Fraser et al., 2018).

Pelagic *Sargassum* occurs over vast areas of open ocean but is patchy and ephemeral. Its distribution is largely controlled by physical processes, notably ocean circulation and wind (Brooks et al., 2018). *Sargassum* accumulates in areas of convergence, similar to debris and other pollutants (Powers et al., 2013). Monitoring of pelagic *Sargassum* is constrained by lack of basic information on its life history, demography, and responses to environmental conditions. The broad distribution and drifting of *Sargassum* also presents challenges for monitoring. Since 2011, large rafts of *Sargassum* have entered the Caribbean Sea, washing ashore in massive amounts and affecting navigation and the economies of the island nations in the region, which are largely driven by tourism and, to a lesser extent, fishing. *Sargassum* accumulation and pollution often co-occur, threatening the endemic and other species that rely on *Sargassum* (Witherington et al., 2012; Powers et al., 2013). The ecological implications of these accumulations are poorly studied (van Tussenbroek et al., 2017; Gavio and Santos-Martinez, 2018). In the short term, *Sargassum* can suffocate coastal fauna by depleting dissolved oxygen as the algal biomass decomposes, stress coral reefs by shading their photosynthetic symbionts, and render sea turtle nesting beaches unusable. But moderate influx of biomass and marine-derived nutrients may enhance the growth of dune vegetation and stabilize coastlines. Understanding such ecological processes is necessary for informed management decisions.

MARINE VEGETATION, ECOSYSTEM SERVICES, AND HUMAN WELL-BEING

Ecosystem services are benefits that humans receive from the Earth's natural systems and include provisioning, regulating, cultural, and supporting processes (Costanza et al., 1997; Rapport et al., 1998; MEA, 2005). In coastal ecosystems, marine macrophytes provide services including fisheries support, nutrient cycling, coastal protection, water purification, provision of raw materials, and carbon storage that can counteract climate change (Geider et al., 2001; Boström et al., 2003; UNEP, 2006; Bos et al., 2007; Cullen-Unsworth and Unsworth, 2013; Vassallo et al., 2013; Campagne et al., 2015; Dewsbury et al., 2016; Nordlund et al., 2016; Lamb et al., 2017; Filbee-Dexter and Wernberg, 2018). Because seagrasses are sensitive to nutrient loading and water transparency, they also serve as valuable indicators of the state of coastal ecosystems (Dennison, 1987). Seagrasses contribute to water quality by reducing pathogens that cause disease in corals and humans (Lamb et al., 2017) and by taking up nutrient runoff from land. They protect coastal lives and property by stabilizing coastal sediments via both their below-ground rhizome structure and leaf canopies (Cruz-Palacios and Van Tussenbroek, 2005; Bos et al., 2007). Seagrass ecosystems are also increasingly recognized as protecting underwater cultural heritage (Krause-Jensen et al., 2018).

Similarly, macroalgal forests provide a range of ecosystem services (Vásquez et al., 2014; Bennett et al., 2016; Macreadie et al., 2017; Blamey and Bolton, 2018), including direct support of commercial, recreational, and subsistence fisheries and aquaculture. Indirect ecosystem services include erosion control, climate change mitigation and adaptation, and biogeochemical cycling of nitrogen, carbon, and phosphorus. Intrinsic ecosystem services include cultural and religious significance, biodiversity, and scientific value. Cultural services provided by macrophytes remain understudied (Ruiz-Frau et al., 2017) but include tourism, aesthetic values, and some traditional ways of life that are intricately associated with these ecosystems for food, recreation, and spiritual fulfillment (Wyllie-Echeverria et al., 2002; de la Torre-Castro and Rönnbäck, 2004; Cullen-Unsworth and Unsworth, 2013; Filbee-Dexter and Wernberg, 2018). Few studies have valued macroalgal ecosystem services economically (Bennett et al., 2016), but laminarian kelp forests have been estimated to contribute around 1 million USD per kilometer of coastline (Filbee-Dexter and Wernberg, 2018). The true value is likely to be orders of magnitude higher if indirect and non-use values are fully considered (Bennett et al., 2016).

Marine Macrophytes and Fisheries

Marine macrophytes provide critical habitat that supports fisheries' productivity and food security across the world, especially in developing regions (Beck et al., 2001; Green and Short, 2003; Orth et al., 2006; Brun et al., 2009; Unsworth et al., 2014; Nordlund et al., 2016, 2018; Unsworth R. et al., 2018). In the Mediterranean, for example, seagrass covers <2% of the seafloor but seagrass-associated fishes and invertebrates comprise 30–40% of the total value of commercial fisheries landings (Jackson et al., 2015). Shallow seagrass meadows are easily exploitable and support subsistence, commercial, or recreational fishing in many regions, ranging from hand-gleaning to commercial trawling and targeting multiple fish and invertebrate species (Nordlund et al., 2018). Kelp forests similarly serve as nurseries for fished species in some regions (Hamilton and Konar, 2007). Some kelp ecosystems have been overfished (Tegner and Dayton, 2000; Bertocci et al., 2015), but knowledge of these fisheries is geographically limited. Other marine macrophytes are also important for fisheries (Kritzer et al., 2016), including tropical seaweed beds (Tano et al., 2016, 2017). The increasing human populations and standards of living in developing nations put a premium on maximizing the productivity and sustainability of fisheries generally and on conserving the marine macrophyte habitats that support them (Unsworth R. et al., 2018). There is a strong need to include the value of seagrass and macroalgal habitats in spatial planning and management (Nordlund et al., 2018; Unsworth R. et al., 2018). Finally, pelagic *Sargassum* also has been designated an "essential fish habitat" (NOAA, 1996), as it provides shelter and food for early life-stages of pelagic fishes (Wells and Rooker, 2004) and may play an important role in the recruitment dynamics of economically important species (Kingsford and Choat, 1985).

Carbon and Nutrient Storage by Marine Macrophytes

Marine ecosystems play key roles in mitigating rising atmospheric CO_2 by sequestering and storing carbon in coastal plant biomass and sediments—known as "blue carbon." Seagrass meadows, tidal marshes, and mangrove forests are key blue carbon habitats, occupying just 1% of the seafloor but storing over half the ocean's carbon (Duarte et al., 2013), sequestering much more carbon on a per-area basis than terrestrial vegetated ecosystems (Mcleod et al., 2011; Röhr et al., 2018). But the magnitude of this carbon storage is highly variable (Nelleman, 2009; Kennedy et al., 2010; Mcleod et al., 2011; Kindeberg et al., 2018; Röhr et al., 2018). Macroalgae form the most extensive of marine vegetated habitats, but until recently were overlooked as contributors to carbon sequestration because they are mostly confined to rocky substrata that do not support carbon burial in sediments (Howard et al., 2017). However, macroalgal forests can export material to carbon sinks in shelf sediments and in the deep sea where it can be sequestered (Krumhansl and Scheibling, 2012; Hill et al., 2015; Krause-Jensen and Duarte, 2016; Wernberg and Filbee-Dexter, 2018). A first-order estimate indicates that this macroalgal contribution is of the same order of magnitude as carbon sequestration by seagrasses, saltmarshes, and mangroves combined (Krause-Jensen and Duarte, 2016). The contribution of macroalgae to carbon sequestration varies among species (Trevathan-Tackett et al., 2015), but more direct estimates are needed to quantify sequestration, and this requires a paradigm shift in accounting procedures as well as development of methods to trace carbon from donor to sink habitats in the ocean (Krause-Jensen et al., 2018). As vegetated ecosystems have declined substantially in area (Waycott et al., 2009), many coastal areas have been converted from carbon sinks to sources, a shift that can, in principle, be reversed (Pendleton et al., 2012; Macreadie et al., 2015, 2017; Marbà et al., 2015; Kerrylee et al., 2018). One approach to quantifying the processes that mediate carbon storage and release from seagrass sediments is the TeaComposition H_2O project, which uses widely available tea bags to measure organic carbon preservation in seagrass and other wetland sediments, currently under way across 350 nearshore marine sites. Similarly, the SUKER Network has recently completed globally distributed litterbag experiments across 40 sites between Alaska and Portugal to measure the fate of sugar kelp detritus.

Anthropogenic nitrogen inputs are a major stressor facing coastal ecosystems worldwide (Duarte et al., 2009). Historically, nitrogen has been a limiting factor for primary production in many coastal regions, but nutrient loading from agricultural runoff and coastal development has greatly increased usable nitrogen availability in coastal systems worldwide. These inputs shift the character of the vegetation and produce far-reaching impacts that ripple through coastal ecosystems (Breitburg et al., 2009). Macrophytes can help mitigate such eutrophication. Seagrass meadows suffer less decline where they are separated from terrestrial runoff by fringing marshes, probably because of denitrification and burial of terrestrial nitrogen within the marshes before it reaches the seagrasses offshore (Valiela and Cole, 2002). Seaweed aquaculture also has been proposed as a way to mitigate eutrophication impacts (Chopin et al., 2001; Neori et al., 2004), and in certain locations on the coast of China, algal cultivation has reduced nutrients and resulting algal blooms, including toxic microalgae (Yang et al., 2014). But algal aquaculture has more often been detrimental, resulting in widespread seagrass loss (Eklöf et al., 2006; Unsworth R. K. et al., 2018).

Marine Macrophytes and Animal Species of Conservation Concern

Macrophyte ecosystems provide food and habitat to a wide range of invertebrates, fishes, and some marine mammals and reptiles, including several listed under CITES [e.g., the dugong, *Dugong dugon;* the West Indian manatee, *Trichechus manatus;* and the African manatee, *Trichechus senegalensis*, all listed in CITES Appendix 1, and the green turtle, *Chelonia mydas*, classified as Endangered on the IUCN Red List and also on CITES Appendix 1 (Moore et al., 2017; Sievers et al., 2019)]. Most large animals that depend on seagrasses have declined substantially during historical times, and about 30% of named seahorse species, all of which use seagrass habitats, are included on the IUCN Red List (Hughes et al., 2009). Prior to European colonization, large seagrass-feeding vertebrates were extremely abundant in some regions. The Cayman Islands fishery in the Caribbean landed ~13,000 sea turtles each year for decades beginning in the late Seventeenth century (Jackson, 1997), and the number of dugongs along the coast of the Great Barrier Reef Region south of Cairns was much greater than it is today (Marsh et al., 2005). The formerly larger densities of megaherbivores undoubtedly had major impacts on seagrasses (Marsh et al., 2011, 2018; Vonk et al., 2015), but megaherbivore grazing can also increase seagrass productivity (Aragones and Marsh, 2000; Christianen et al., 2011; Marsh et al., 2011, 2018). Live seagrass seeds have been found in megaherbivore feces, indicating the potential for green turtles and dugongs to disperse seeds up to hundreds of kilometers (Tol et al., 2017) and excavating dugongs can also increase microbial nutrient cycling in seagrass sediments (Perry and Dennison, 1999). Megaherbivores associated with seagrasses also support provisioning and cultural ecosystem services, including hunting, fishing, tourism, and cultural values (Butler et al., 2012; Cullen-Unsworth et al., 2014).

Large-scale loss of seagrass results in mortality and reduced fecundity of seagrass-dependent megaherbivores (Marsh et al., 2011; Fuentes et al., 2016). Kelp forests of the northeastern Pacific formerly supported the largest known herbivorous marine mammal, Steller's sea cow (*Hydrodamalis gigas*). This giant 8–9 m relative of the dugong was hunted to extinction within a few decades of its first encounter with Europeans in 1741 (Marsh et al., 2011), and the sea otter (*Enhydra lutris*) nearly met a similar fate, having been eliminated from the North Pacific apart from a few remote islands of the Aleutian chain prior to protection in the 1970s. There is some evidence of a symbiotic relationship between sea otters and seagrasses (Hughes et al., 2013).

As is true of marine invertebrates generally, we have very limited knowledge of the conservation status of most macrophyte-associated invertebrates. Several gastropods and echinoderms are popular as curios and traditional medicines, and harvesting may contribute to their population decline or extinction (Hughes et al., 2009).

Pelagic *Sargassum* serves as nursery habitat for oceanic-stage juvenile sea turtles (Carr, 1987; Witherington et al., 2012). Young turtles likely grow faster in association with pelagic *Sargassum* owing to foraging on invertebrates in the algae and higher temperatures achieved by basking in surface rafts, and the thick mats may also reduce predation risk (Mansfield and Putman, 2013; Mansfield et al., 2014). In 2014, the US National Marine Fisheries Service designated waters in the U.S. Exclusive Economic Zone with abundant pelagic *Sargassum* as a "critical habitat" for the loggerhead sea turtle (*Caretta caretta*) in the Northwest Atlantic Ocean. There is also growing evidence that small sea turtles of several species actively orient toward pelagic *Sargassum* (Mansfield and Putman, 2013; Putman and Mansfield, 2015). New satellite-based mapping (**Figures 2A,C**) now makes it possible to integrate *Sargassum* distribution with models of sea turtle behavior and movement (Putman et al., 2012) to explore its role in turtle population dynamics.

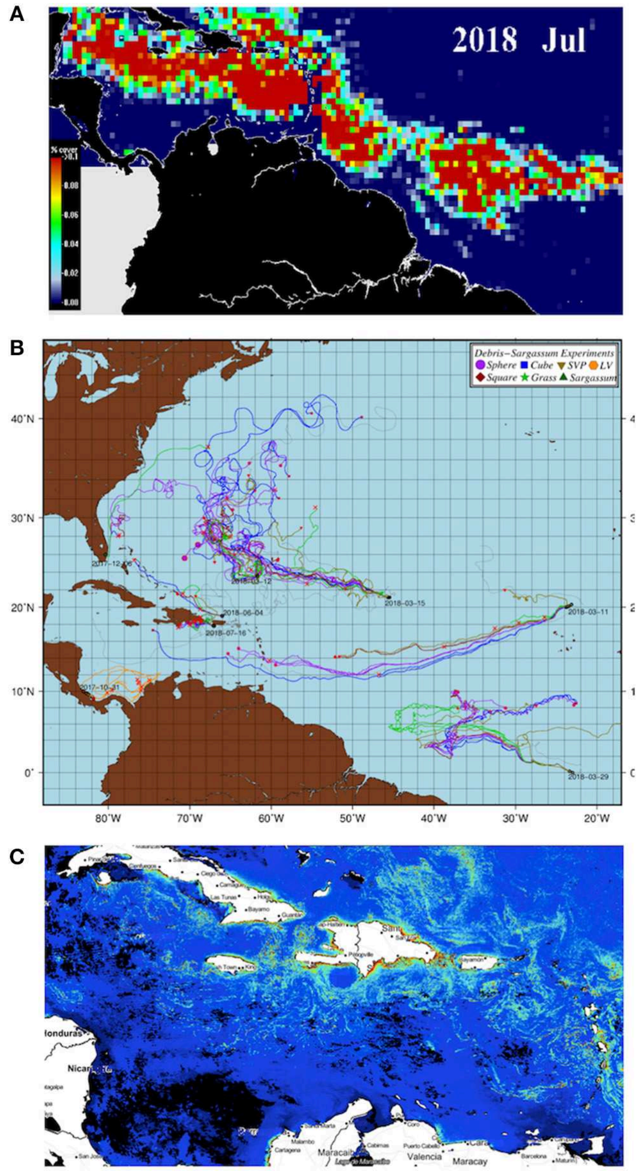

FIGURE 2 | Tracking of pelagic *Sargassum* density and movement in the Caribbean region. **(A)** *Sargassum* area density map (0.5° × 0.5°) in July 2018. The red color indicate pixels where the area density (% cover) exceeds 0.1 units. **(B)** Trajectories of spatial drifters deployed by NOAA/AOML in the Atlantic. Each color represents a type of drifter. The trajectories of drifters with transmitters attached to real and artificial *Sargassum* are shown in green. **(C)** Cumulative weekly AFAI field from VIIRS&MODIS (20 June 2018). The structures in green/red may correspond to *Sargassum* patches, which extended over large areas in the Caribbean Sea during that period. Clouds are masked to black.

Marine Macrophytes and Coastal Protection

In addition to their role in climate change mitigation through carbon storage, marine macrophytes also contribute to climate change adaptation e.g., by dampening the wave energy and stimulating sedimentation, thereby protecting coastlines against rising water levels and storms (Duarte et al., 2013). Coastal wetlands, including seagrass meadows and some macroalgal forests, form protective barriers that shelter coastal land from erosion and storm surge by attenuating waves and reducing property damage and human deaths. Both living plants and their dead biomass accreted as peat strengthen shorelines and provide a robust barrier that protects coastal land against sea level rise (Gedan et al., 2011), severe storms, and wave action. Analysis of 34 major US hurricanes found that economic damage declined with greater area of wetland in the storm zone, and that wind speed and wetland area together explained 60% of the variation in damage; coastal wetlands were estimated to provide more than 23 billion USD per year in storm protection in the USA (Costanza et al., 2008). And studies in the UK concluded that maintenance of natural marsh is much less expensive than building and maintaining sea walls as protection against erosion (King and Lester, 1995; Rupprecht et al., 2017).

Mapping the risk of storm and wave hazards along the coastline of the USA shows that, under several projected climate scenarios, the number of people and the total value of residential property exposed to hazards could be reduced by half by preserving existing coastal habitats (Arkema et al., 2013). Models predict that climate change will increase wave heights, especially at higher latitudes (Izaguirre et al., 2011). In Northern Europe, the intensity of destructive storms has already increased more than 3-fold since 1990 (Gregow et al., 2017), and monthly mean wave heights have risen up to 0.6 m in the North Atlantic during the latter twentieth century (Woolf et al., 2002). Natural infrastructure provided by coastal habitats holds strong but understudied potential to mitigate such hazards and increase coastal resilience under climate change (Sutton-Grier et al., 2015).

OBSERVATION SYSTEMS FOR MACROPHYTES

Current Status of Observing: Seagrasses

To examine the current status of marine macrophyte observing, we collated information on monitoring programs with more than three repeated observation events over a period >3 years, with a least one observation event in the last decade (2008–2018). This eliminated the large number of localized, short-term monitoring projects. Of the 20 active long-term seagrass observing programs meeting these criteria (**Table S1**), the largest were the global programs SeagrassNet and Seagrass-Watch. Together these programs include long-term monitoring across five of the six seagrass bioregions (**Figure 1**), with 21 countries currently participating in SeagrassNet and 11 in Seagrass-Watch. One of the largest regional networks is in the temperate North Atlantic region, where 23 countries monitor seagrass via 11 programs (e.g., COMBINE; PMN) (Marbà et al., 2013) in compliance with the pan-European Water Framework Directive (WFD, 2000/60/EC) (Foden and Brazier, 2007). The WFD stimulated widespread monitoring of macroalgae and seagrasses in Europe by prescribing assessment of ecological status based on biological elements, including aquatic plants. However, while the WFD requires that ecological status is defined relative to a reference, and that status classifications are intercalibrated within ecoregions, member states are free to develop their own indicators, which has resulted in a proliferation of seagrass indicators that are often not comparable (Krause-Jensen et al., 2005; Marbà et al., 2013).

The motivations for existing seagrass observing networks range from broad—increasing general scientific knowledge and tracking the status of seagrass—to more narrow efforts to support conservation and regulatory agreements. The book *Global Seagrass Research Methods* (Short and Coles, 2001) provides detailed methodology for assessing all aspects of seagrass ecosystems. Two broad approaches are currently used to monitor seagrass ecosystems. The first involves air-borne or satellite remote sensing to map seagrass and estimate broad-scale changes in extent over time. The second approach quantifies indicators of seagrass condition *in situ* at smaller spatial scales, often to assess the effects of stressors. These approaches have been powerfully combined in a hierarchical framework for monitoring based on spatial extent, frequency of monitoring, and scope (Neckles et al., 2012). The first tier within the hierarchical framework characterizes overall distribution of seagrasses across a region of interest. This approach is widely used to assess status and trends at broad scales, over long time periods, with low observing frequency. Aerial and hyperspectral satellite imagery are well-established techniques at such scales, but such remote technology restricts observations to shallow depths and is often unworkable in the complex multi-habitat seascapes and turbid waters where seagrasses are most abundant (Knudby and Nordlund, 2011). Measures derived from remote sensing are often limited to presence/absence and extent. Rapidly evolving technological advances may offer partial solutions, with improvements in resolution and availability of both satellite sensors and high-quality drone and autonomous or remotely operated sensors (both above and within water) increasing the environmental window of opportunity for observing and quantifying seagrass. Currently, there is no consistent approach or recommended sensor for seagrass globally.

Some observing networks supplement remote sensing with *in situ* manual sampling of species identity and abundance, which constitute the second and subsequent tiers within a hierarchical monitoring framework. *In situ* sampling characterizes seagrass condition by selecting statistically rigorous sampling units and monitoring frequency, e.g., SeagrassNet. These measurements are predominantly *in situ* and done by hand, providing more detailed indicators of spatiotemporal variation in species composition, size, and abundance (e.g., cover, density, biomass). These second-tier measures involve a greater number of sampling units, a higher temporal frequency, and higher resolution than the first tier of remote sensing. Finer-scale tiers generally focus more specifically on evaluating drivers of change at higher frequency, with more metrics, and a smaller number of sites. These *in situ* methods are far more accurate and detailed than remote sensing but accordingly more labor intensive and thus restricted in scope.

The GOOS has proposed harmonization of monitoring protocols toward development of seagrass cover and composition as an Essential Ocean Variable (Miloslavich et al., 2018). Several collective decisions need to be made to achieve this goal. First, there is currently no widely accepted standard for site selection, and observing networks vary widely in the types, sizes, and replication of sampling and reporting units. Most networks use some version of stratified random sampling, with or without constraints. For example, areas of investigation are often divided using expert knowledge into subpopulations—e.g., by water depth—that maximize variation between and minimize the variation within units. Sampling units are then randomly drawn and may be allocated proportionately to provide robust estimates of variance (Neckles et al., 2012; see also FKMMP, Texas Seagrass Monitoring program). This approach aims to balance reporting area size, level of detail necessary, accessibility, legacy, safety, and budget.

Once the reporting unit or site is established, the second decision to be considered involves the frequency of assessment and sampling design. Current long-term observing networks generally monitor annually, with a few including seasonal assessments. Networks that use a hierarchical framework generally make observations at a lower frequency for the first large-scale tier (e.g., 3–5 years), with annual and seasonal monitoring for the smaller-scale sampling tiers. Some networks (e.g., Seagrass-Watch) implement an adaptive monitoring approach, altering the frequency of monitoring and data collection when rates of change differ from those initially anticipated, or when the focus of investigation changes. The most popular spatial study design generally involves sampling along a transect. This design has advantages over random sampling in being easier, more cost effective, in guaranteeing that measurements are evenly spread, and in being able to sample a given plot repeatedly through time. The number of samples necessary to characterize a reporting unit also depends on the variance of the indicator of interest.

The third decision involves selecting among the many indicators used to evaluate seagrass ecosystem status across spatial scales, species, and habitats. The plethora of indicators and indices (Marbà et al., 2013) complicates both comparisons across ecosystems and the choice of optimal monitoring strategy. But a recent analysis of the sensitivity and response time of various indicators to ecosystem degradation and recovery formed the basis for a decision tree for selecting indicators to assist managers for specific management goals (Roca et al., 2016). The best established and most commonly used measure of seagrass abundance is percent cover estimated visually. Percent cover has wide application and can reduce overall sampling error because it is simple and promotes replication. Estimating cover can be subjective, but use of common reference cards, QA/QC procedures, and clear criteria can greatly improve the accuracy of cover estimates (Finn et al., 2010). Quadrat measurements of percent cover are more efficient in detecting change in seagrass cover than seagrass blade counts or above- or below-ground biomass measures, and the latter require destructive sampling (Heidelbaugh and Nelson, 1996). It is possible to estimate seagrass biomass from cover after field quantification of biomass-cover relationships (Carstensen et al., 2016). Additional indicators measured within the sampling unit may include seagrass species identity and diversity, shoot characteristics, chemical constituents, and associated flora and fauna. A few programs include process indicators such as productivity, herbivore pressure, flowering reproductive effort, and/or or recovery capacity via seed banks or shoot recruitment. Finally, some seagrass functional types and traits are more sensitive to stressors than others, which can be used in an evidence-based approach to selecting appropriate and reliable indicators for specific management goals (Roca et al., 2016).

Remote sensing and *in situ* sampling provide complementary views of seagrass habitat. Remote sensing across heterogeneous reporting areas often cannot detect habitat distribution changes <30% (Lee Long et al., 1996; Unsworth et al., 2009; Hossain et al., 2010; Schultz et al., 2015). Such programs require ground-truthing to increase precision and accuracy. The level of change and accuracy of detection vary across programs. There is an urgent need to design more effective monitoring capable of detecting change of 10% or less (Duarte, 2002). Approaches that use fixed plots have higher statistical power for detecting small changes compared with random-plot methods (Schultz et al., 2015). The tiered approach that links remote sensing to *in situ* sampling systematically offers promising solutions to this challenge (Neckles et al., 2012).

Numerous environmental drivers influence seagrass occurrence and persistence in an area (Short et al., 2014). These include the biophysical parameters that regulate physiological activity and morphology (water depth, salinity, light, temperature, nutrients, etc.), biological parameters such as herbivory and diseases, and anthropogenic impacts that inhibit plant growth such as excess nutrients and sediments. Almost all observing networks include some measure of water quality, including salinity, temperature, and/or light. Some networks implement continuous monitoring of key pressures (e.g., temperature and light) via relatively inexpensive loggers, which improves interpretation of environmental influence on seagrass condition. Other measures commonly collected include sediment condition, such as grain size and organic content (Short and Coles, 2001).

Current Status of Observing: Benthic Macroalgal Forests

Numerous programs monitor macroalgal forests (**Table S1**), but coverage is patchy. Many regions have not been surveyed (Krumhansl et al., 2016) because they do not have the required infrastructure or funding and/or are inaccessible. Surveying these areas is difficult because many occur in cold, turbid, deep, and/or wave-exposed environments far from road access. For mapping distributions, some of these challenges can be overcome with remote surveying, including drones (Konar and Iken, 2018) and aerial photography. Satellites are promising for mapping of intertidal algae in particular (Brodie et al., 2018; Setyawidati et al., 2018). For kelps that form surface canopies, the Landsat series of satellites provides a record back to 1983 at 30-m resolution (Cavanaugh et al., 2011; Nijland et al., 2019) and more recent satellites provide even higher resolution (Cavanaugh et al., 2010). However, canopy-forming kelps on low-contrast bottoms or in deeper or turbid water can be difficult to see from the air, and some canopies (e.g., *Nereocystis leutkeana*) vary in visibility with tides. Satellite imagery has limited effectiveness for the many areas without surface kelp. Kelps can now be detected to a depth of 6 m (Uhl et al., 2016), but this only covers a portion of their depth range. Sidescan sonar is one promising technique for differentiating species (Cochrane and Lafferty, 2002; Dijkstra et al., 2017). Automated sensing of macrophyte beds by autonomous underwater vehicles (AUVs) also shows promise. Aerial UAVs have proven effective for macroalgae monitoring on intertidal reefs (Murfitt et al., 2017). As with remote sensing generally, ground-truthing is often needed to determine what lies beneath the surface.

While the general features of intertidal macroalgal communities can be surveyed from boats or aerial imagery, e.g., via the CARLIT method used in the Mediterranean (Blanfun et al., 2016), most benthic macroalgal forests cannot be detected from the air and efficient underwater surveying methods are essential. Large-scale mapping of the most conspicuous species can be done with drop-down camera imagery from a boat, video surveys by SCUBA divers aided by diver propulsion vehicles (DPVs) (Kimura et al., 2012), and AUVs (Barrett and Edgar, 2010; Bewley et al., 2015). SCUBA diver-operated cameras may be more versatile, but AUVs have more autonomy in remote areas. For long and remote coastlines, predictive modeling of marine macrophyte species distributions can be a strong aid to indicate the most likely places for species to occur as a basis for the spatial design of field campaigns and ground-truthing (Bekkby et al., 2009). Finally, programs based on volunteers can be useful analyzing or taking images for presence/absence (e.g., www.marineforests.com; https://seagrassspotter.org). Such citizen science initiatives can cover broad spatial areas because they allow participation by persons anywhere in the world as long as they have access to the internet and can photograph the appropriate organisms.

Remote surveys based on imagery often cannot distinguish species or quantify their abundances. For such purposes, scuba is usually necessary, which entails finer spatial scales. As is true for seagrasses, many surveys of macroalgae apply transect approaches with nested quadrat sampling. Recording abundances in the field saves time and space in sample processing. However, complete surveys of seaweed diversity or small recruit density can only be done with microscopic analyses. Thus, if the goals include both broad and fine-scale biodiversity or recruitment surveys, the optimal solution might be a stratified sampling design, with different resolution of sampling at different spatial scales, as described above for seagrasses (Neckles et al., 2012).

Many macroalgal forests are highly dynamic across time and space (Krumhansl et al., 2016), so long-term monitoring is needed to parse out spatial and temporal variability from longer-term directional change. As is also true for seagrasses, most macroalgal monitoring programs follow protocols that fit their local situation logistically and financially, and thus use different sampling designs, replication, taxonomic resolution, and frequency, making inter-regional comparisons difficult. Lack of consensus on the nature and the need for reference conditions has also resulted in inconsistencies in the way anthropogenic effects have been assessed and interpreted. For example, the CARLIT approach uses macroalgal assemblages from pristine areas (e.g., marine protected areas in Sardinia and the Balearic Islands in the Mediterranean) as a reference condition for assemblages on the mainland (Ballesteros et al., 2007b; Asnaghi et al., 2009). Although this can be a powerful approach to identify relatively pristine locations (as suggested by high similarity between focal and reference assemblages), it ignores the potential confounding effect of geographic segregation and the inherent differences between islands and the mainland (Benedetti-Cecchi et al., 2003). This contrasts with design-based approaches, such as Before-After/Control-Impact (BACI) designs and their evolution (Underwood, 1994), that require the interspersion of focal and reference conditions to tease apart anthropogenic influences from the effect of spatially confounding factors. From 2000–2010, the Census of Marine Life attempted to compare intertidal and shallow subtidal macroalgal forests globally using a common protocol that quantified biomass. This was very expensive and time-consuming, but resulted in some global comparisons (Cruz-Motta et al., 2010; Konar et al., 2010), with some sites still sampled today.

Current Status of Observing: Pelagic *Sargassum*

Due to its vast and largely inaccessible habitat in the open ocean, pelagic *Sargassum* is monitored mostly by satellite (Brooks et al., 2018). Satellite sensors are a valuable tool in a wide range of applications, including coastal mapping, ocean circulation monitoring, resource management, and extreme event forecasting (**Table 1**). The combination of spatial, temporal, spectral, and radiometric resolution of different satellite sensors helps define the potential uses of each sensor. Usually, and for ocean dynamic monitoring purposes, the feature size stretches between submesoscale (0.1–10 kilometers) and mesoscale (10–100 kilometers), with required revisit times between a few hours to a few days in most cases (Sentinel-3: ESA's Global Land and Ocean Mission for GMES Operational Services-ESA SP-1322/3, October 2012).

Practical monitoring and tracking of pelagic *Sargassum* uses two main satellite-derived products, the Alternative Floating Algae Index (AFAI) and the Maximum Chlorophyll Index (MCI). Both are based on the radiance/reflectance measured above a baseline interpolated between 2 neighboring spectral bands (Gower and King, 2011; Wang and Hu, 2016). The objective is to detect surface algal accumulations, identifying the patches and long lines of *Sargassum*. This information could then be used to study *Sargassum* distribution and variability and to predict beaching events. To obtain accurate and reliable results, invalid pixels must be masked for clouds, cloud shadows, sun-glint areas, sensor zenith areas, etc. The satellite core observational component (**Table 1**) consists of various sensors, such as the Moderate Resolution Imaging Spectroradiometer (MODIS) on Terra and Aqua and the Medium Resolution Imaging Spectrometer (MERIS) onboard the Envisat-1 satellite. Follow-up ocean color missions ensure the continuity of the time series, especially after Envisat-1 was lost in April 2012, and both MODIS satellites have exceeded their expected lifetime by several years. The Ocean Land Color Instrument (OLCI) onboard the Sentinel-3 constellation and the Visible Infrared Imaging Radiometer Suite (VIIRS) on the Joint Polar Satellite System (JPSS) satellites are multispectral radiometers that, besides their other multiple ocean color applications, also contribute to providing global and low latency information on *Sargassum* (Wang and Hu, 2018).

Satellite data miss small patches of *Sargassum* at subpixel scale. Higher resolution satellite fields, such as the Floating Algae Index (FAI) obtained from OLI on Landsat-8 and other pseudo-color imagery decrease this gap at the cost of reducing coverage, revisiting times, and often larger latencies and processing times. An optimized solution would require implementing a synergistic approach in the integration of diverse datasets, including high-resolution, low-altitude airborne measurements.

The Satellite-based Sargassum Watch System (SaWS) at the University of South Florida (USF) relies on near-real-time satellite and modeling results to detect and track pelagic *Sargassum* fields, which serve to create monthly outlook bulletins, showing the distribution and coverage maps in the Central West Atlantic (CWA) and Caribbean regions (Hu et al., 2016). These monthly *Sargassum* density maps (**Figure 2A**) are used to predict *Sargassum* blooms in the Caribbean Sea from AFAI observations in a hotspot region in the CWA (Wang and Hu, 2016). USF AFAI fields are also served through the Atlantic OceanWatch node, hosted at AOML, which provides cumulative daily, 3-day, and weekly datasets within an interoperable framework (**Figure 2B**).

As is true for seagrasses and kelp forests, field observations are essential to calibrating and validating satellite measurements, reducing the uncertainties and adding value to the satellite products (e.g., tuning regional algorithms). For pelagic *Sargassum*, geolocated visual observations (i.e., from ships, aircrafts, shore) serve as a valuable proxy of ground-truthing to test the satellite algorithms. Sites such as the one implemented by the Gulf Coast Research Laboratory collect *Sargassum* observation details online. The samples of *Sargassum* provide information about the abundance and distribution, and the opportunity to carry out genetic and morphological analysis. The Sea Education Association (SEA) has been collecting *Sargassum* samples using dip nets and surface neuston tows for more than 40 years in the Sargasso Sea, Caribbean and Gulf of Mexico. This dataset contributes to the study of the annual and interannual distribution of pelagic *Sargassum*.

As mentioned above, the effects of currents and winds in the distribution of pelagic *Sargassum* are not well-understood. The Atlantic Oceanographic and Meteorological Laboratory (NOAA/AOML) is currently conducting an experiment (**Figure 2B**) where undrogued drifters of various sizes and shapes, simulating common debris and *Sargassum*, were deployed in the Atlantic to assess the impact of wind and currents on their trajectories. These drifters are tracked in real time using GPS transmissions.

The scale of satellite remote sensing of drifting marine macrophytes requires coordinated, ongoing efforts involving multiple connecting stakeholders across government, academia, industry, and civil society, some of which have already been organized. Through a coordinated multi-disciplinary initiative, including interaction between scientists, data providers, environmental managers and decision makers, a practical monitoring system and accompanying *Sargassum* warning strategies are in development. The Spatial Data Infrastructure (SDI) component relies on products obtained from *in situ* and remote sensing data, specifically developed to detect and track *Sargassum*; numerical prediction models to determine potential trajectories and volumes; and interoperable tools. The benefits of this framework span essential economic, social, and environmental domains, defining the baseline needed to coordinate future science-driven monitoring and evaluation efforts. A pilot project for this effort is currently in place and led by IOCARIBE of IOC UNESCO, the GEO Blue Planet Initiative, UNDP Barbados and the Organization of East Caribbean States with partners from government agencies, intergovernmental initiatives, and academia, and with continued improvements expected to benefit the populations and economies of the countries in the region and beyond.

Commonalities Among Systems

Summary of Current Observing Systems

Primary goals of macrophyte observing programs include tracking status and trends in macrophyte abundance and extent as well as understanding the environmental and anthropogenic forcing of these patterns. Generally, this approach involves spatial and temporal analyses to detect change relative to benchmarks and to predict future trajectories. Observation systems take a variety of approaches depending on goals and targeted species and often differ in spatial and temporal scales, frequency of sampling, and taxonomic resolution (**Tables S1a,b**). Most programs for benthic macrophytes employ some form of area-based sampling, typically using quadrats of 0.25 m^2 or more, nested within larger transects of 20–100 meters. The size of the sampled patches and transects depends greatly on programmatic goals and the physical and biological characteristics of the systems. Temporal coverage also varies (**Tables S1a,b**), with most observation systems focused primarily on longitudinal surveys at regional or sub-regional scales over many years (or seasons; e.g., MexCal). Other programs have focused on broad spatial coverage at some expense to temporal coverage (e.g., Reef Life Survey, RLS). Repeated surveys are done through fixed transects in some programs, such as the Santa Barbara Coastal Long Term Ecological Research (SBC LTER) Project and the Channel Islands Kelp Forest Monitoring, ensuring the same spaces are re-sampled annually. Other programs use stratified random sampling within sites to assess variability over time at site, but not small scales, such as in MarClim (Mieszkowska et al., 2006, 2014) and the Kelp Ecosystems Ecology Network (KEEN; www.kelpecosystems.org).

TABLE 1 | Main sensors being used to detect and track pelagic *Sargassum*.

Sensor	Satellite	Parameter	Spatial resolution	Comments
MERIS	Envisat-1 (2002-2012)	MCI	300 m/1.2km	Revisit time: 3 days
MODIS	Terra (2000-)/Aqua(2002-)	AFAI	250 m/1.2km	Revisit time ∼ daily
VIIRS	SNPP(2012-)/NOAA-20(2018-)	AFAI	750 m	Revisit time ∼ daily JPSS-2 (2021), JPSS_3(2026), JPSS-3(2031)
OLCI	Sentinei-3A(2016-)/Sentinel-38(2018-)	MCI	300 m/1.2km	Revisit time ∼ 1-2 days (2-satellites)
OLI	Landsat-8(2013-)	FAI	30 m	Revisit time=16 days Landsat-9(2020)

Primary and Associated Variables

Public funding for macrophyte monitoring is ultimately motivated by interest in management of fisheries and other ecosystem services to humans. Robust Ecosystem-Based Management (Curtin and Prellezo, 2010) requires consideration of interactions among organisms within food webs. Indicators applied in EBM typically include abundances of fishes and larger invertebrates, and in some cases metrics of trophic transfer, functional diversity, and population sizes of key species. These variables generally require large logistical effort and often destructive sampling. Visual survey techniques are commonly used for fishes and include quantitative diver transects (Edgar and Stuart-Smith, 2014; Norderhaug et al., 2015), various versions of Remote Underwater Video (Langlois, 2006; Perry, 2018), and video captured by AUVs (Ling et al., 2016). Acoustic monitoring is also increasingly possible (Kaartvedt et al., 2009). As for most sampling, a combination of methods can reduce biases of individual methods (Edgar et al., 2016) and likely provides the best strategy for sampling a diverse range of biota. The requirements for effective ecosystem-based management of macrophyte systems are beyond the scope of this review, but we note that this is an important goal of macrophyte observing and should inform strategies for system design (Personnic et al., 2014; Thibaut et al., 2017).

Knowledge Products and End-Users

To be useful to management, a biodiversity observing system must produce integrated data products and concise, intuitive ways to convey variability and uncertainty to non-scientific audiences. Managers generally need integrated data summaries with concrete information related to the missions of their agencies. Users of such products include institutional decision makers, environmental managers, and stakeholders in the fisheries, aquaculture, and tourism sectors. Common information needs are for status and trends in extent and condition of habitat and of commercially important, charismatic, or protected species and quality of water and environment. The Chesapeake Bay Program and the Great Barrier Reef Marine Monitoring Programme exemplify successful efforts to communicate results of seagrass status and trends to the wider general public using easily interpretable scorecards (McKenzie et al., 2017). Such approaches are invaluable for maintaining support and buy-in from stakeholders and the general public.

The usefulness of monitoring for decision makers depends on a framework for interpreting indicators of change in systems or species relevant to the question of interest (Markiewicz and Patrick, 2015). For example, do changes to a system have positive or negative consequences for people, what are the causes, and can they be reversed or mitigated? In addition to the magnitude and direction of changes, managers need guidance on risks, opportunities, and likelihood of success of different mitigating and remediating actions. Observing systems can also inform proactive planning for sustainable development and conservation by providing the spatial data necessary to evaluate benefits and trade-offs associated with different management options. For instance, Strategic Environmental Assessments (SEAs) and Environmental Impact Assessments (EIAs) require access to such data in order to inform policies and programs related to spatial planning, and whether to permit proposed development activities. Other management programs that require information generated by long-term sustained monitoring efforts include the Condition Reports produced by the National Marine Sanctuaries, and the Integrated Ecosystem Assessment (IEA) developed by the National Oceanic and Atmospheric Administration (NOAA) in the USA. These considerations emphasize that a key aspect of designing and managing an integrated observing network is involving stakeholders and a sustained focus on how the field measurements are translated to informative and useful indicators for management.

Opportunities and Emerging Technologies

Metagenomics and eDNA

Molecular tools show promise for tackling several long-standing challenges in macrophyte monitoring. Molecular tools can screen environmental samples where no macrophytes are visible, identify species presence, and even roughly quantify them under certain conditions (Chariton et al., 2010; Pawlowski et al., 2011). DNA fingerprinting of individual organisms after local extinctions can identify whether new recruits arise from the local population or from immigration (Assis et al., 2017). A key need in realizing the great potential for screening environmental samples is developing improved reference libraries for marine macrophytes.

An inherent challenge to long-term biodiversity monitoring is changing taxonomy, which is happening rapidly for macroalgae as a result of new insights from DNA-based analyses and improved collections. Cryptic species, which may be indistinguishable without molecular methods, are common in macroalgae as they are in marine invertebrates (Knowlton, 1993). Molecular tools can be integrated into observing systems to provide sharper identification, revealing new macroalgal species along coastlines studied by PISCO in California (Neiva et al., 2017) and MarClim in the UK (Zardi et al., 2015) for example.

A related application of molecular tools is environmental DNA (eDNA) obtained from water or other environmental samples that originated in biological materials shed by organisms (Bourlat et al., 2013; Thomsen and Willerslev, 2015). Where sufficient sequence libraries exist to identify this material, eDNA can be used to confirm current or recent presence of organisms not detected by other methods. In the marine environment, eDNA has been used primarily to detect microbes and viruses, eukaryotic phytoplankton, zooplankton, macro-invertebrates, and vertebrates (Djurhuus et al., 2018; Goodwin et al., 2019). But eDNA has also been used to confirm the historic presence of seagrass at locations where it no longer exists (Hamaguchi et al., 2018). The only other study using eDNA from marine plants of which we are aware estimated the contribution of seagrasses and macroalgae to carbon stocks in sediments (Reef et al., 2017). Developing DNA barcoding resources for seagrasses and macroalgae that are suitable for eDNA approaches could greatly advance macrophyte observing systems. It is essential that such studies are cross-referenced with high quality sequence libraries connected to voucher specimens lodged in museums or herbaria (Dormontt et al., 2018). A complete DNA reference library for seagrasses is being developed by the Global Initiative to Barcode Seagrass (GIBS) (http://barcoding.seagrassonline.org/) and is more than 50% completed.

Molecular tools are also promising for inferring drivers of spatial connectivity important in management, such as those observed for giant kelp in the Santa Barbara Channel Long-Term Ecological Research site (Alberto et al., 2011; Johansson et al., 2015); for seagrasses in the Caribbean (van Dijk et al., 2018) and North Atlantic (Olsen et al., 2004); and for locating particularly rich and threatened biodiversity hotspots (Assis et al., 2018). Analysis of molecular markers in a phylogeographic context has helped understand pathways of marine animal migration (Taberlet et al., 2012) and can be similarly useful for tracking drifting macrophytes (Fraser et al., 2018; Smith et al., 2018). Molecular tools may also prove useful in characterizing genetic diversity and changes in seaweed species used in aquaculture (Valero et al., 2017).

Remote Sensing and Telemetry

Remote sensing provides unique opportunities for observing marine macrophytes. First, while *in situ* monitoring protocols are well-established for seagrasses, slow change in some species results in shifting baselines (Pauly, 1995) that make detecting change difficult (Unsworth et al., 2014), and *in situ* studies are highly patchy in time and space. Improvements in and lower cost of remote sensing technology, and accessibility of satellite imagery are advancing the ability to map seagrass extent (Fortes et al., 2018). Remote sensing is a promising means of mapping seagrass cover in shallow areas with clear water (Kendrick et al., 2002; McCarthy et al., 2018; Traganos and Reinartz, 2018), but it is much more difficult in the optically complex environments of turbid estuaries and where smaller species dominate. This is a key frontier for future research and technology development.

Second, remote sensing provides one of the only realistic ways to get approximate estimates of macrophyte extent in remote or poorly resourced regions. In recent decades, satellite sensor technology has developed rapidly, as has the availability of high-resolution multispectral imagery (Hossain et al., 2015). Further research is expected to improve the application of such technologies to seagrass remote sensing. No single technology can currently measure all seagrass parameters of interest, particularly at small scales, but knowledge of seagrass distribution is increasing rapidly as a result of more widely available high-resolution imagery and increasing interest in seagrass worldwide. Remote sensing may help address the key frontier of knowledge inequality between the global North and South if approaches can be better developed to suit the conditions in poorly known and resourced regions of the southern hemisphere, including high seagrass diversity, complex multi-habitat seascapes, and deep water. This approach will also require active participation of local contributors.

In Southeast Asia, for example, regional-scale estimates of seagrass extent have only recently emerged. This is primarily a result of advancements in remote sensing technology and well-funded regional projects such as the UNEP/GEF South China Sea Project, the Bay of Bengal Large Marine Ecosystem Project, and the JSPS-Asian CORE Project (Fortes et al., 2018) and the Blue Carbon Project of the Coral Triangle. Large-scale assessments are often extrapolated based on environmental conditions, with relatively low resolution (often 10 km pixels), and can produce suspect estimates of macrophyte cover and habitat suitability on local scales, particularly for animals. Such estimates need refinement but are a valuable start for poorly known and resourced regions.

Remote sensing is the primary means of tracking pelagic *Sargassum*, estimating monthly mean biomass of at least 4.4 million tons drifting in the Caribbean Sea and Central West Atlantic in July 2015 (Hu et al., 2015; Wang et al., 2018). Combining molecular markers with oceanographic circulation models can identify movement and dispersal patterns of drifting algae and associated organisms across the ocean surface (Fraser et al., 2018). Tracking mats of *Sargassum*, as well as other drifting macrophytes, could be facilitated with attached GPS devices that relay position via satellite, particularly by deploying paired drifters alongside *Sargassum* mats, drogued at different depths to track and quantify divergence between *Sargassum* and ocean currents (**Figures 2B,C**). Similar work conducted with small sea turtles (Putman and Mansfield, 2015) greatly improved predictions of their distribution in particle-tracking dispersal models (Putman et al., 2015). Such coordination of targeted *in situ* sampling with remotely sensed observations of *Sargassum* and numerical modeling would help refine and validate inferences from satellite-based observations. For pelagic *Sargassum*, a key research area is determining the effects of transport within the upper few meters of the ocean, prioritizing research through sensitivity analyses (Putman et al., 2018). For example, predicting the timing and location of *Sargassum* beaching over a period of a few weeks might be highly sensitive to wind activity in the Caribbean Sea. Such modeling analyses could help prioritize aspects of transport for empirical investigations.

Machine Learning

The advent of new massive data collection systems, computers with enhanced processing and storage capabilities, and algorithms to parse and structure data offers a set of powerful emerging technologies that can be deployed in biodiversity observations. Machine Learning (ML) is a subset of Artificial Intelligence and aims to identify meaningful patterns and associations in data and use them to produce models that can predict future outcomes. One of the most promising ML techniques is Deep Learning, usually linked to its popular architecture, Deep Neural Networks (DNN). New ML frameworks such as TensorFlow and PyTorch implement DNNs that can be easily applied to diverse classification and regression problems. In oceanography and satellite data processing, artificial neural networks have been applied intensively only in the last few years. Multiple applications include modeling and predicting pathogen outbreaks (Wang and Deng, 2016), SAR image classification (Bentes et al., 2015), fish detection and recognition (Villon et al., 2016), ocean color product generation (Hieronymi et al., 2017), satellite biogeographic seascape classifications (Kavanaugh et al., 2016), carbon flux estimates (Laruelle et al., 2017), the drift paths of massive blooms of *Ulva prolifera* (Hu et al., 2018), and species recognition in images from diver visual surveys (Edgar et al., 2016). For pelagic *Sargassum* monitoring, ML techniques could be applied to estimate total biomass, analyze environmental factors driving growth and distribution, develop "sensorless" classification models to identify S*argassum* in remote imagery, and predict trajectories.

DATA MANAGEMENT AND DISTRIBUTION

Access to relevant, high-quality data is critical to informing sustainable management and use of the ocean. But there are many challenges to achieving consistent and intercomparable data flows at the scale and accuracy required, including differing quality, time frames, scales, and resolutions. Methods of data collection may affect the interoperability and interpretation of data for use in decision-making. Biodiversity monitoring efforts tend to be widely distributed, challenging the production of a global, or even regional understanding of ecosystem states. Conceptual frameworks such as the Essential Biodiversity Variables (EBVs) and the EOVs can help to generate interoperable, multi-purpose data based on common monitoring protocols (Muller-Karger et al., 2018). These data can be made available in centrally accessible, open-access repositories such as IOC-UNESCO's Ocean Biogeographic Information System (OBIS; www.iobis.org), which is linked to more than 20 regional OBIS nodes and 500 organizations worldwide, facilitating integration of observations—in this case, more than 45 million—to support marine biodiversity assessments. Data uploaded into OBIS have the additional benefit of becoming automatically available on the Global Biodiversity Information Facility (GBIF). These global databases are integrated with herbarium data, literature record compilations, and citizen science image-based records at www.marineforests.com. In any such large-scale database it is important to consult taxonomic specialists and regional experts to curate and validate data before using, because misidentification of species in the published literature is a challenging and common problem in many macrophyte groups.

One challenge to better integration and standardization of biodiversity data is defining a common language. Protocols such as the Extended Darwin Core, adopted by OBIS and GBIF, offer standardized and stable sets of terms to facilitate publishing and sharing of information about biological diversity by providing reference definitions and examples (Wieczorek et al., 2012). The Darwin Core Archive (DwC-A) provides taxonomic and spatially explicit information on species occurrences, while the "extended" version provides flexibility to adapt the Darwin Core to include additional information. Standards such as these should be complemented by detailed metadata, specification of data sources and methods used, and the attributed license and any use restrictions. Recent progress has been made toward fewer and more user-friendly data licenses, reducing the uncertainty surrounding how data may be used. Most notably, Creative Commons licenses (http://creativecommons.org) have made licenses more readily accessible, understandable and easily adopted by content providers, including those who distribute data.

Another major challenge to realizing a world of open data is fair credit for work and data generation (Wilkinson et al., 2016). Given the proliferation of data, it has become difficult to track the use of data in subsequent work and for data providers to demonstrate impact in the same way as those who publish peer-reviewed papers, despite the considerable effort involved in generating these data. Increasingly, digital object identifiers (DOIs) have been adopted by data publishers to provide permanent links to the original sources of data, helping to track how these data are being used in subsequent research through citations. The attribution of DOIs by data publishers thereby offers data contributors the ability to track and demonstrate their impact. This practice is also being adopted by journals (e.g., *Nature Scientific Data*, which provides both a paper DOI and a data DOI). Ultimately, we need multi-purpose, interoperable approaches that allow consolidation of data in meaningful ways while ensuring appropriate attribution for data providers and clarity regarding how these data can be used. Recent advances toward establishing consistent approaches globally will help to make quality data available and inform decision making at multiple scales.

LESSONS LEARNED AND RECOMMENDATIONS

Macrophytes are diverse, and the observation systems that study them similarly vary widely in nature and sophistication (Miloslavich et al., 2018). Some are run by governments, with strong training, retention of personnel, and long-term stability. Others are collaborative networks of multiple academic institutions (e.g., Partnership for Interdisciplinary Studies of Coastal Oceans, or PISCO). Some are spearheaded by a few key personnel (e.g., MarClim) and work with local partners and citizen scientists (e.g., RLS, Seagrass Watch, www.marineforests.com). Our review suggests several themes for advancing these diverse efforts toward a global network that achieves more than the sum of its parts.

The Future Is Distributed

Tremendous efforts are already ongoing to monitor seagrass, kelp, and pelagic *Sargassum* abundance and distribution, but these efforts are poorly coordinated and use a wide variety of methods that are often not comparable. There is much added value to be gained with relatively modest investment in building and sustaining platforms for easy communication, collaboration, knowledge sharing, and training. An important lesson from the Census of Marine Life is the need for common protocols to capture change across multiple scales in space and time. Only by ensuring comparability can we generate the expansive datasets needed to address variation at scales relevant to environmental management, including the pervasive effects of global climate change.

Keep It Simple

The long-term seagrass observing networks that have persisted are those that have purpose-built approaches and methods that can be consistently conducted with modest funding and person-power (**Table S1**). Approaches that are robust and usable across a variety of seascapes, taxa, and habitats are most accessible to diverse contributors and regions. A simple, standardized core field sampling architecture can then provide a scaffolding for integration—and ground-truthing—of new technology, including remote sensing, machine learning techniques for species recognition from imagery, and eDNA, when and where resources are available. Given the number of methods available, aims need to be clearly defined to assess trade-offs between data resolution and monitoring feasibility.

Keep It Relevant

Achieving widespread community buy-in for coordinated monitoring of marine macrophytes will be advanced by clearly linking observing activities to the needs of local participants, policy makers, and decision makers. The data collected need to be scientifically rigorous enough for acceptance by policy makers but simple enough to be conducted widely and communicated clearly to the general public. Coordination among efforts will also increase efficiency and add value. Better coordination and mapping of macrophyte extent and quality would advance initiatives to develop integrated seagrass accounts that map ecosystem services and value them as natural capital. Building a clearly articulated natural capital base for marine macrophytes could open doors to new funding streams by linking ecosystem services to end users (e.g., fishers, carbon traders, tourist industry). For example, Essential Ocean Variables for marine macrophytes could link to blue carbon initiatives, which have the potential to develop a commercial user base and supplementary funding.

Focus on Contributors

Any long-term project will experience lapses in funding, leadership, and/or other interruptions, and most rely on substantial leveraging of in-kind support from participants. To sustain an observing system under such circumstances, it is imperative that the work addresses local needs, builds capacity and community, and provides opportunities across career levels, including future generations. Local participants must also feel ownership and a degree of control if efforts are to be sustained. These results can be met with an approach based on a standardized but flexible sampling design and protocols that provide a scaffolding on which additional activities of local interest can be built and that catalyzes and adds value to those activities. For example, implementing a standard seagrass monitoring protocol often provides opportunities for participants to quantify commercially important species during the same surveys, provides educational opportunities to local students, and so on. An important component of all observing networks is feedback and outreach. Not only is this critical for networks that rely on voluntary data contributions, but it ensures project outputs remain useful for evidence-based policy and management decisions. Sustaining a network of monitoring sites ultimately requires strong collaborations in addition to knowledge and technology transfer among participating observatories. This is especially urgent in Small Island Developing States and Least Developed Countries, where the knowledge gaps are largest and coastal ecosystems are particularly vulnerable. This is a core goal of the Group on Earth Observations Biodiversity Observation Networks (Pereira et al., 2013). Similarly, GOOS aims to tackle this challenge by promoting standardized protocols and data management best practices (Bax et al., 2018).

In many regions, Local Ecological Knowledge (LEK) can provide unique data to establish baselines and to understand historical change (Johannes et al., 2000; Beaudreau and Levin, 2014; Frans and Auge, 2016; Aswani et al., 2018), as it often incorporates observations over longer time periods and preserves memories of rare and extreme events (Moller et al., 2004). LEK can also be used to direct exploratory scientific sampling efforts. Engaging fishers and other users specifically can take advantage of their regular access to the sea (Hashim et al., 2017; Cullen-Unsworth et al., 2018). A combination of science and LEK can provide data across larger temporal and spatial scales. LEK and associated citizen science have been increasingly applied to help map and monitor marine habitats, including seagrasses, at global scales in cost-effective ways (Titilola, 1990; Moller et al., 2004; Jones et al., 2017) and to help design marine protected areas (Ban et al., 2009). Such approaches also provide opportunities for engagement, empowerment, and an improved sense of well-being. The capacity for LEK to contribute to large-scale ocean observation systems remains largely untapped. Finally, citizen-based monitoring can provide valuable data under the right circumstances (McKenzie et al., 2000; Short et al., 2006), although it is difficult to implement in regions where macrophytes are submerged and inaccessible.

Provide Support and Training

Reliable replication over space and time and rigorous standardization are essential in any monitoring program aimed at detecting changes. Providing support, training, coordination, and data management for monitoring is a challenge for all long-term observing networks as they face periods of reduced funding, which can compromise data quality. A key part of support is consistent and sustainable training tools and protocols for new technicians and other members to ensure consistent application of methods over time and space. Some networks have institutionalized training or require passing courses (e.g., KEEN, PISCO, Reef Life Survey, and MBON Pole to Pole), a model that should be widely adopted.

Ensure Continuity

Sustaining observing efforts over the long term requires plans for continuity of leadership, funding, training, and data management. In most networks, a small number of champions act as a driving force, and there is little planning for succession and turnover. Such plans are needed to sustain any program through the long-term. The Kelp Forest Monitoring program provides a valuable model in that it has successfully turned over leadership twice in its multi-year lifespan, in part due to such planning.

Expand the Reach

Nearly all monitoring programs are conducted by marine scientists or environmental practitioners. However, over the last couple of decades, citizen science has also begun to contribute significantly to science, education, and policy (Jones et al., 2017). Citizen monitoring is most successful when it requires minimal specialized equipment and resources. Nearly a third of the current long-term seagrass observing networks include some level of citizen science, including SeagrassWatch and SeagrassSpotter.org as well as TeaComposition H_2O. The incorporation of approaches based on Information and Communication Technology (ICT) into citizen science expands its reach. By using a web and phone app approach, SeagrassSpotter.org has to date collected data in 75 countries and included observations of 36 species, and www.marineforests.com includes thousands of photographic records around the world. Citizen science is also included in the Kelp Ecosystem Ecology Network. In Southeast Asia, citizen initiatives are key to the effective linkage between science, policy, and practice, which is the core of coastal natural resources management (Fortes et al., 2018).

Data Management, Ownership, and Access

Observing systems are only as good as the data produced. Collection, storage, and use of data must be designed with a long-term vision, engaging global institutions to ensure data security and accessibility. To assure users of data quality, observing networks should implement clear, formal, and transparent practices for quality assurance and quality control (QA/QC) and data management. Data management is opaque for many current long-term monitoring programs, with only a few having centralized systems and even fewer with clear QA/QC protocols. Clear and transparent policies on data ownership and procedures for data access are also critical for any observing network (Wilkinson et al., 2016), particularly when it includes multiple contributors from many organizations. Implementing standard data agreements facilitates confidence among data collectors, stewards, and users.

Promote Rigorous Taxonomic Standards

Comparisons across space and time can be challenging where taxonomic expertise is inadequate. Some observation systems target only major structure-forming taxa, while others sample a much broader taxonomic range. Increasing taxonomic depth is time consuming and expensive, and the inherent tradeoff between sampling scale and taxonomic depth is a key hurdle to harmonizing biological observation efforts. The level of taxonomic resolution also depends strongly on the knowledge of system participants. One possible solution involves strong, independent cross-verification of identifications based on archived voucher collections. Methods based on imagery have the advantage of being independently verified by other observers in future analyses. Photographs and voucher collections have been particularly important in cases where species names change as cryptic species are discovered (Zardi et al., 2015; Neiva et al., 2017). Thus, archiving images and voucher collections makes surveys more valuable. Formal systems for classifying functional groups (Althaus et al., 2015) would advance cross-system comparisons, including across temperate and tropical systems. Achieving harmonized strategies for aligning taxonomic or functional levels, good management of leadership, methodologies, training, and data management, should not only produce more effective and efficient observing in practice but will facilitate a more accurate global picture of change in macrophyte systems. Such efforts should incorporate rigorous documentation and open-access archiving of protocols and all stages of workflow, from field surveys to data management (e.g., through Ocean Best Practices), and provide open access data.

Adopt an Ecosystem Approach

Over the last decade or so, fisheries have increasingly explored, and sometimes adopted, an ecosystems approach (Travis et al., 2014; Patrick and Link, 2015), recognizing that harvested species are connected via a web of complex interactions with abiotic forcing and other species that may confound management based on simpler models. The same situation holds for coastal vegetation (Duffy et al., 2013b). Long-term observations have confirmed that decline in coastal macrophyte ecosystems resulted from both excess nutrient loading and altered food webs resulting from harvesting in the Baltic Sea (Eriksson et al., 2011) and California (Hughes et al., 2013). These examples emphasize the need for an ecosystem-based approach to coastal resource management and that this requires management—and monitoring—of multiple biological and environmental variables.

The substantial prior efforts devoted to monitoring and research on seagrasses, macroalgal forests, and pelagic *Sargassum* offer several valuable lessons for envisioning a more ambitious, coordinated effort in support of a global observing system. Successful observing programs are driven by tractable questions with rigorous, common statistical designs that meet specific scientific and policy needs. Long-term observation projects for coastal seagrasses and macroalgae have been substantially under-resourced relative to observations of oceanic phytoplankton despite the outsized importance of coastal vegetation in fisheries support, coastal protection, global carbon dynamics, and other ecosystem services. A key, achievable goal is to reach consensus on when, where, and how methods can be harmonized to provide a minimal set of common metrics, agreed sampling designs, and data reporting mechanisms and standards that build toward global coverage. Implementing a robust large-scale observation network should consider the past, with the wealth of legacy data and LEK available, the shifting baselines of the present, and focus attention proactively on the range of possible future outcomes for the health and ecosystem services provided by seagrass meadows, macroalgal forests, and pelagic *Sargassum*.

AUTHOR CONTRIBUTIONS

JD, LB-C, JT, and FM-K developed the project idea and coordinated writing and editing. LM and JB led assembly of network data for **Table S1**. All authors contributed to manuscript writing and/or editing.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2019.00317/full#supplementary-material

REFERENCES

Alberto, F., Raimondi, P. T., Reed, D. C., Watson, J. R., Siegel, D. A., Mitarai, S., et al. (2011). Isolation by oceanographic distance explains genetic structure for *Macrocystis pyrifera* in the santa barbara channel. *Molecul. Ecol.* 20, 2543–2554. doi: 10.1111/j.1365-294X.2011.05117.x

Althaus, F., Hill, N., Ferrari, R., Edwards, L., Przeslawski, R., Schönberg, C. H. L., et al. (2015). A standardised vocabulary for identifying benthic biota and substrata from underwater imagery: the CATAMI classification scheme. *PLoS ONE* 10:e0141039. doi: 10.1371/journal.pone.0141039

Altizer, S., Ostfeld, R. S., Johnson, P. T. J., Kutz, S., and Harvell, C. D. (2013). Climate change and infectious diseases: from evidence to a predictive framework. *Science* 341, 514–519. doi: 10.1126/science.1239401

Aragones, L., and Marsh, H. (2000). Impact of dugong grazing and turtle cropping on tropical seagrass communities. *Pacific Conserv. Biol.* 5, 286–288. doi: 10.1071/PC000277

Araujo, R. M., Assis, J., Aguillar, R., Airoldi, L., Barbara, I., Bartsch, I., et al. (2016). Status, trends and drivers of kelp forests in Europe: an expert assessment. *Biodivers. Conserv.* 25, 1319–1348. doi: 10.1007/s10531-016-1141-7

Arkema, K. K., Guannel, G., Verutes, G., Wood, S. A., Guerry, A., Ruckelshaus, M., et al. (2013). Coastal habitats shield people and property from sea-level rise and storms. *Nat. Clim. Chang.* 3, 913–918. doi: 10.1038/nclimate1944

Asnaghi, V., Chiantore, M., Bertolotto, R. M., Parravicini, V., Cattaneo-Vietti, R., Gaino, F., et al. (2009). Implementation of the European water framework directive: natural variability associated with the CARLIT method on the rocky shores of the Ligurian Sea (Italy). *Mar. Ecol. Evol. Persp* 30, 505–513. doi: 10.1111/j.1439-0485.2009.00346.x

Assis, J., Araujo, M. B., and Serrao, E. A. (2018). Projected climate changes threaten ancient refugia of kelp forests in the North Atlantic. *Global Change Biol.* 24, E55–E66. doi: 10.1111/gcb.13818

Assis, J., Berecibar, E., Claro, B., Alberto, F., Reed, D., Raimondi, P., et al. (2017). Major shifts at the range edge of marine forests: the combined effects of climate changes and limited dispersal. *Sci. Rep.* 7. doi: 10.1038/srep44348

Assis, J., Coelho, N. C., Lamy, T., Valero, M., Alberto, F., and Serrao, E. A. (2016). Deep reefs are climatic refugia for genetic diversity of marine forests. *J. Biogeogr.* 43, 833–844. doi: 10.1111/jbi.12677

Assis, J., Serrao, E. A., Claro, B., Perrin, C., and Pearson, G. A. (2014). Climate-driven range shifts explain the distribution of extant gene pools and predict future loss of unique lineages in a marine brown alga. *Mol. Ecol.* 23, 2797–2810. doi: 10.1111/mec.12772

Aswani, S., Lemahieu, A., and Sauer, W. (2018). Global trends of local ecological knowledge and future implications. *PLoS ONE* 13:e0195440. doi: 10.1371/journal.pone.0195440

Baden, S., Boström, C., Tobiasson, S., Arponen, H., and Moksnes, P.-O. (2010). Relative importance of trophic interactions and nutrient enrichment in seagrass ecosystems: a broad-scale field experiment in the Baltic-Skagerrak area. *Limnol. Oceanogr.* 55:1435. doi: 10.4319/lo.2010.55.3.1435

Ballesteros, E., Cebrian, E., and Alcoverro, T. (2007a). Mortality of shoots of *Posidonia oceanica* following meadow invasion by the red alga *Lophocladia lallemandii*. *Botan Marina* 50, 8–13. doi: 10.1515/BOT.2007.002

Ballesteros, E., Torras, X., Pinedo, S., García, M., Mangialajo, L., and de Torres, M. (2007b). A new methodology based on littoral community cartography dominated by macroalgae for the implementation of the European Water Framework Directive. *Mar. Pollut. Bull.* 55, 172–180. doi: 10.1016/j.marpolbul.2006.08.038

Ban, N. C., Picard, C. R., and Vincent, A. C. J. (2009). Comparing and integrating community-based and science-based approaches to prioritizing marine areas for protection. *Conserv. Biol.* 23, 899–910. doi: 10.1111/j.1523-1739.2009.01185.x

Barrett, N. S., and Edgar, G. J. (2010). Distribution of benthic communities in the fjord-like Bathurst Channel ecosystem, south-western Tasmania, a globally anomalous estuarine protected area. *Aquat. Conserv.* 20, 397–406. doi: 10.1002/aqc.1085

Bax, N. J., Appletans, W., Brainard, R., Duffy, J. E., Dunstan, P., Hanich, Q., et al. (2018). Linking capacity development to monitoring networks to achieve sustained ocean observation. *Front. Mar. Sci.* 5:346. doi: 10.3389/fmars.2018.00346

Beaudreau, A. H., and Levin, P. S. (2014). Advancing the use of local ecological knowledge for assessing data-poor species in coastal ecosystems. *Ecol. Appl.* 24, 244–256. doi: 10.1890/13-0817.1

Beck, M. W., Heck Jr., K. L., Able, K. W., Childers, D. L., Eggleston, D. B., Gillanders, B. M., et al. (2001). The identification, conservation, and management of estuarine and marine nurseries for fish and invertebrates. *Bioscience* 51, 633–641. doi: 10.1641/0006-3568(2001)051<0633:TICAMO>2.0.CO;2

Bekkby, T., Rinde, E., Erikstad, L., and Bakkestuen, V. (2009). Spatial predictive distribution modelling of the kelp species *Laminaria hyperborea*. *ICES J. Mar. Sci.* 66, 2106–2115. doi: 10.1093/icesjms/fsp195

Benedetti-Cecchi, L., Maggi, E., Bertocci, I., Vaselli, S., Micheli, F., Osio, G. C., et al. (2003). Variation in rocky shore assemblages in the northwestern Mediterranean: contrasts between islands and the mainland. *J. Exp. Mar. Biol. Ecol.* 293, 193–215. doi: 10.1016/S0022-0981(03)00220-X

Benedetti-Cecchi, L., Pannacciulli, F., Bulleri, F., Moschella, P. S., Airoldi, L., Relini, G., et al. (2001). Predicting the consequences of anthropogenic disturbance: large-scale effects of loss of canopy algae on rocky shores. *Mar. Ecol. Prog. Ser.* 214, 137–150. doi: 10.3354/meps214137

Benedetti-Cecchi, L., Tamburello, L., Maggi, E., and Bulleri, F. (2015). Experimental perturbations modify the performance of early warning indicators of regime shift. *Curr. Biol.* 25, 1867–1872. doi: 10.1016/j.cub.2015.05.035

Bennett, S., Wernberg, T., Connell, S. D., Hobday, A. J., Johnson, C. R., and Poloczanska, E. S. (2016). The 'Great Southern Reef': social, ecological and economic value of Australia's neglected kelp forests. *Mar. Freshwat. Res.* 67, 47–56. doi: 10.1071/MF15232

Bentes, C., Velotto, D., and Lehner, S. (2015). "Target classification in oceanographic SAR images with deep neural networks: Architecture and initial results," in *2015 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, 3703–3706. doi: 10.1109/IGARSS.2015.7326627

Bertocci, I., Araujo, R., Oliveira, P., and Sousa-Pinto, I. (2015). REVIEW: potential effects of kelp species on local fisheries. *J. Appl. Ecol.* 52, 1216–1226. doi: 10.1111/1365-2664.12483

Bewley, M. S., Nourani-Vatani, N., Rao, D., Douillard, B., Pizarro, O., and Williams, S. B. (2015). Hierarchical classification in AUV imagery. *Springer Trac. Adv. R.* 105, 3–16. doi: 10.1007/978-3-319-07488-7_1

Blamey, L. K., and Bolton, J. J. (2018). The economic value of South African kelp forests and temperate reefs: past, present and future. *J. Mar. Syst.* 188, 172–181. doi: 10.1016/j.jmarsys.2017.06.003

Blanfun,é, A., Boudouresque, C. F., Verlaque, M., Beqiraj, S., Kashta, L., Nasto, I., et al. (2016). Response of rocky shore communities to anthropogenic pressures in Albania (Mediterranean Sea): ecological status assessment through the CARLIT method. *Mar. Pollut. Bull.* 109, 409–418. doi: 10.1016/j.marpolbul.2016.05.041

Bonsdorff, E., Blomqvist, E. M., Mattila, J., and Norkko, A. (1997). Coastal eutrophication: causes, consequences and perspectives in the Archipelago areas of the northern Baltic Sea. *Est. Coast. Shelf Sci.* 44, 63–72. doi: 10.1016/S0272-7714(97)80008-X

Bos, A. R., Bouma, T. J., de Kort, G. L. J., and van Katwijk, M. M. (2007). Ecosystem engineering by annual intertidal seagrass beds: Sediment accretion and modification. *Est. Coast. Shelf Sci.* 74, 344–348. doi: 10.1016/j.ecss.2007.04.006

Boström, C., Baden, S., and Krause-Jensen, D. (2003). "The seagrasses of Scandinavia and the Baltic Sea," in *World Atlas of Seagrasses: Present Status and Future Conservation*, eds E. Green, F. Short, and M. Spalding (Berkley: California Press), 27–37.

Bourlat, S. J., Borja, A., Gilbert, J., Taylor, M. I., Davies, N., Weisberg, S. B., et al. (2013). Genomics in marine monitoring: new opportunities for assessing marine health status. *Mar. Pollut. Bull.* 74, 19–31. doi: 10.1016/j.marpolbul.2013.05.042

Breitburg, D. L., Craig, J. K., Fulford, R. S., Rose, K. A., Boynton, W. R., Brady, D. C., et al. (2009). Nutrient enrichment and fisheries exploitation: interactive effects on estuarine living resources and their management. *Hydrobiologia* 629, 31–47. doi: 10.1007/s10750-009-9762-4

Brodie, J., Ash, L. V., Tittley, I., and Yesson, C. (2018). A comparison of multispectral aerial and satellite imagery for mapping intertidal seaweed communities. *Aquat. Conserv.* 28, 872–881. doi: 10.1002/aqc.2905

Brodie, J., Williamson, C. J., Smale, D. A., Kamenos, N. A., Mieszkowska, N., Santos, R., et al. (2014). The future of the northeast Atlantic benthic flora in a high CO 2world. *Ecol. Evol.* 4, 2787–2798. doi: 10.1002/ece3.1105

Brooks, M. T., Coles, V. J., Hood, R. R., and Gower, J. F. (2018). Factors controlling the seasonal distribution of pelagic Sargassum. *Mar. Ecol. Prog. Ser.* 599, 1–18. doi: 10.3354/meps12646

Brun, F. G., van Zetten, E., Cacabelos, E., and Bouma, T. J. (2009). Role of two contrasting ecosystem engineers (*Zostera noltiiand Cymodocea nodosa*) on the food intake rate of *Cerastoderma edule*. *Helgol. Mar. Res.* 63, 19–25. doi: 10.1007/s10152-008-0134-7

Burkholder, J., Tomasko, D., and Touchette, B. (2007). Seagrasses and eutrophication. *J. Exp. Mar. Biol. Ecol.* 350, 46–72. doi: 10.1016/j.jembe.2007.06.024

Buschmann, A. H., Camus, C., Infante, J., Neori, A., Israel, A., Hernandez-Gonzalez, M. C., et al. (2017). Seaweed production: overview of the global state of exploitation, farming and emerging research activity. *Eur. J. Phycol.* 52, 391–406. doi: 10.1080/09670262.2017.1365175

Butler, J. R. A., Tawake, A., Skewes, T., Tawake, L., and McGrath, V. (2012). Integrating traditional ecological knowledge and fisheries management in the torres strait, Australia: the catalytic role of turtles and dugong as cultural keystone species. *Ecol. Soc.* 17:34. doi: 10.5751/ES-05165-170434

Campagne, C. S., Salles, J.-M., Boissery, P., and Deter, J. (2015). The seagrass *Posidonia oceanica*: ecosystem services identification and economic evaluation of goods and benefits. *Mar. Pollut. Bull.* 97, 391–400. doi: 10.1016/j.marpolbul.2015.05.061

Carpenter, K. E., Abrar, M., Aeby, G., Aronson, R. B., Banks, S., Bruckner, A., et al. (2008). One-third of reef-building corals face elevated extinction risk from climate change and local impacts. *Science* 321, 560–563. doi: 10.1126/science.1159196

Carr, A. (1987). New perspectives on the pelagic stage of sea turtle development. *Conserv. Biol.* 1, 103–121. doi: 10.1111/j.1523-1739.1987.tb00020.x

Carstensen, J., Krause-Jensen, D., and Balsby, T. J. S. (2016). Biomass-cover relationship for eelgrass meadows. *Est. Coasts* 39, 440–450. doi: 10.1007/s12237-015-9995-6

Cavanaugh, K., Cavanaugh, K. C., Siegel, D. A., and Reed, D. C. (2011). Environmental controls of giant-kelp biomass in the Santa Barbara Channel, California. *Mar. Ecol. Progr. Seri. Oldendorf.* 429, 1–17. doi: 10.3354/meps09141

Cavanaugh, K. C., Cavanaugh, K., Siegel, D., and Kinlan, B. P. (2010). Scaling giant kelp field measurements to regional scales using satellite observations. *Mar. Ecol. Progr. Seri. Oldendorf.* 403, 13–27. doi: 10.3354/meps08467

Chariton, A. A., Court, L. N., Hartley, D. M., Colloff, M. J., and Hardy, C. M. (2010). Ecological assessment of estuarine sediments by pyrosequencing eukaryotic ribosomal DNA. *Front. Ecol. Environ.* 8, 233–238. doi: 10.1890/090115

Chefaoui, R. M., Duarte, C. M., and Serrão, E. A. (2018). Dramatic loss of seagrass habitat under projected climate change in the Mediterranean Sea. *Glob. Chang. Biol.* 24, 4919–4928. doi: 10.1111/gcb.14401

Chenelot, H., and Konar, B. (2007). Lacuna vincta (Mollusca, Neotaenioglossa) herbivory on juvenile and adult *Nereocystis luetkeana* (Heterokontophyta, Laminariales). *Hydrobiologia* 583, 107–118. doi: 10.1007/s10750-006-0484-6

Chopin, T., Buschmann, A. H., Halling, C., Troell, M., Kautsky, N., Neori, A., et al. (2001). Integrating seaweeds into marine aquaculture systems: a key toward sustainability. *J. Phycol.* 37, 975–986. doi: 10.1046/j.1529-8817.2001.01137.x

Christianen, M. J. A., Govers, L. L., Bouma, T. J., Kiswara, W., Roelofs, J. G. M., Lamers, L. P. M., et al. (2011). Marine megaherbivore grazing may increase seagrass tolerance to high nutrient loads. *J. Ecol.* 100, 546–560. doi: 10.1111/j.1365-2745.2011.01900.x

Cloern, J. (2001). Our evolving conceptual model of the coastal eutrophication problem. *Mar. Ecol. Prog. Ser.* 210, 223–253. doi: 10.3354/meps210223

Cochrane, G. R., and Lafferty, K. D. (2002). Use of acoustic classification of sidescan sonar data for mapping benthic habitat in the Northern Channel Islands, California. *Cont. Shelf Res.* 22, 683–690. doi: 10.1016/S0278-4343(01)00089-9

Coleman, M. A., Kelaher, B. P., Steinberg, P. D., and Millar, A. J. K. (2008). Absence of a large brown macroalga on urbanized rocky reefs around Sydney, Australia, and evidence for historical decline. *J. Phycol.* 44, 897–901. doi: 10.1111/j.1529-8817.2008.00541.x

Costanza, R., dArge, R., deGroot, R., Farber, S., Grasso, M., Hannon, B., et al. (1997). The value of the world's ecosystem services and natural capital. *Nature* 387, 253–260. doi: 10.1038/387253a0

Costanza, R., Pérez-Maqueo, O., Martinez, M. L., Sutton, P., Anderson, S. J., and Mulder, K. (2008). The value of coastal wetlands for hurricane protection. *Ambio* 37, 241–248. doi: 10.1579/0044-7447(2008)37<241:TVOCWF>2.0.CO;2

Cruz-Motta, J. J., Miloslavich, P., Palomo, G., Iken, K., Konar, B., Pohle, G., et al. (2010). Patterns of spatial variation of assemblages associated with intertidal rocky shores: a global perspective. *PLoS ONE* 5:e14354. doi: 10.1371/journal.pone.0014354

Cruz-Palacios, V., and Van Tussenbroek, B. I. (2005). Simulation of hurricane-like disturbances on a Caribbean seagrass bed. *J. Exp. Mar. Biol. Ecol.* 324, 44–60. doi: 10.1016/j.jembe.2005.04.002

Cullen-Unsworth, L., Jones, B., Seary, R., Newman, R., and Unsworth, R. (2018). Reasons for seagrass optimism: local ecological knowledge confirms presence of dugongs. *Mar. Pollut. Bull.*134, 118–122. doi: 10.1016/j.marpolbul.2017.11.007

Cullen-Unsworth, L., and Unsworth, R. (2013). Seagrass meadows, ecosystem services, and sustainability. *Environment* 55, 14–27. doi: 10.1080/00139157.2013.785864

Cullen-Unsworth, L. C., Nordlund, L. M., Paddock, J., Baker, S., McKenzie, L. J., and Unsworth, R. K. F. (2014). Seagrass meadows globally as a coupled social-ecological system: Implications for human wellbeing. *Mar. Pollut. Bull.* 83, 387–397. doi: 10.1016/j.marpolbul.2013.06.001

Cunha, A. H., Assis, J. F., and Serrão, E. A. (2013). Seagrasses in Portugal: a most endangered marine habitat. *Aquat. Bot.* 104, 193–203. doi: 10.1016/j.aquabot.2011.08.007

Curtin, R., and Prellezo, R. (2010). Understanding marine ecosystem based management: a literature review. *Mar. Policy* 34, 821–830. doi: 10.1016/j.marpol.2010.01.003

Darling, E. S., Alvarez-Filip, L., Oliver, T. A., Mcclanahan, T. R., and Côté, I. M. (2012). Evaluating life-history strategies of reef corals from species traits. *Ecol. Lett.* 15, 1378–1386. doi: 10.1111/j.1461-0248.2012.01861.x

de la Torre-Castro, M., and Rönnbäck, P. (2004). Links between humans and seagrasses - an example from tropical East Africa. *Ocean Coast. Manage.* 47, 361–387. doi: 10.1016/j.ocecoaman.2004.07.005

Dennison, W. C. (1987). Effects of light on seagrass photosynthesis, growth, and depth distribution. *Aquat. Bot.* 27, 15–26. doi: 10.1016/0304-3770(87)90083-0

Dewsbury, B. M., Bhat, M., and Fourqurean, J. W. (2016). A review of seagrass economic valuations: gaps and progress in valuation approaches. *Ecosyst. Serv.* 18, 68–77. doi: 10.1016/j.ecoser.2016.02.010

Dijkstra, J. A., Harris, L. G., Mello, K., Litterer, A., Wells, C., and Ware, C. (2017). Invasive seaweeds transform habitat structure and increase biodiversity of associated species. *J. Ecol.* 105, 1668–1678. doi: 10.1111/1365-2745.12775

Djurhuus, A., Pitz, K., Sawaya, N. A., Rojas-Márquez, J., Michaud, B., Montes, E., et al. (2018). Evaluation of marine zooplankton community structure through environmental DNA metabarcoding. *Limnol. Oceanogr.* 16, 209–221. doi: 10.1002/lom3.10237

Dormontt, E. E., Van Dijk, K., Bell, K. L., Biffin, E., Breed, M. F., Byrne, M., et al. (2018). Advancing DNA metabarcoding applications for plants requires systematic analysis of herbarium collections-an Australian perspective. *Front. Ecol. Evol.* 6:134. doi: 10.3389/fevo.2018.00134

Duarte, C. (1991). Allometric scaling of seagrass form and productivity. *Mar. Ecol. Progr. Seri.* 77, 289–300. doi: 10.3354/meps077289

Duarte, C. M. (1995). Submerged aquatic vegetation in relation to different nutrient regimes. *Ophelia* 41, 87–112. doi: 10.1080/00785236.1995.10422039

Duarte, C. M. (2002). The future of seagrass meadows. *Environ. Conserv.* 29, 192–206. doi: 10.1017/S0376892902000127

Duarte, C. M. (2017). Reviews and syntheses: Hidden forests, the role of vegetated coastal habitats in the ocean carbon budget. *Biogeosciences* 14, 301–310. doi: 10.5194/bg-14-301-2017

Duarte, C. M., Conley, D. J., Carstensen, J., and Sánchez-Camacho, M. (2009). Return to Neverland: shifting baselines affect eutrophication restoration targets. *Estuar. Coasts* 32, 29–36. doi: 10.1007/s12237-008-9111-2

Duarte, C. M., and Krause-Jensen, D. (2017). Export from seagrass meadows contributes to marine carbon sequestration. *Front. Marine Sci.* 4:13. doi: 10.3389/fmars.2017.00013

Duarte, C. M., Losada, I. J., Hendriks, I. E., Mazarrasa, I., and Marbà, N. (2013). The role of coastal plant communities for climate change mitigation and adaptation. *Nat. Clim. Chang.* 3, 961–968. doi: 10.1038/nclimate1970

Duffy, J. E., Amaral-Zettler, L. A., Fautin, D. G., Paulay, G., Rynearson, T. A., Sosik, H. M., et al. (2013a). Envisioning a marine biodiversity observation network. *Bioscience* 63, 350–361. doi: 10.1525/bio.2013.63.5.8

Duffy, J. E., Moksnes, P.-O., and Hughes, A. R. (2013b). "Ecology of Seagrass Communities," in *Marine Community Ecology and Conservation*, eds M. D. Bertness, J. F. Bruno, B. R. Silliman, and J. J. Stachowicz (Sunderland, MA: Sinauer Associates), 271–297.

Edgar, G. J., Bates, A. E., Bird, T. J., Jones, A. H., Kininmonth, S., Stuart-Smith, R. D., et al. (2016). New approaches to marine conservation through the scaling up of ecological data. *Annu. Rev. Mar. Sci.* 8, 435–436. doi: 10.1146/annurev-marine-122414-033921

Edgar, G. J., and Stuart-Smith, R. D. (2014). Systematic global assessment of reef fish communities by the Reef Life Survey program. *Scientific Data* 1:140007. doi: 10.1038/sdata.2014.7

Eklöf, J. S., Henriksson, R., and Kautsky, N. (2006). Effects of tropical open-water seaweed farming on seagrass ecosystem structure and function. *Mar. Ecol. Prog. Ser.* 325, 73–84. doi: 10.3354/meps325073

Eriksson, B. K., Sieben, K., Eklöf, J., Ljunggren, L., Olsson, J., Casini, M., et al. (2011). Effects of altered offshore food webs on coastal ecosystems emphasize the need for cross-ecosystem management. *AMBIO* 40, 786–797. doi: 10.1007/s13280-011-0158-0

Estes, J. A., Heithaus, M., McCauley, D. J., Rasher, D. B., and Worm, B. (2016). Megafaunal impacts on structure and function of ocean ecosystems. *Annu. Rev. Environ. Resourc.* 41, 83–116. doi: 10.1146/annurev-environ-110615-085622

Filbee-Dexter, K., Feehan, C. J., and Scheibling, R. E. (2016). Large-scale degradation of a kelp ecosystem in an ocean warming hotspot. *Mar. Ecol. Prog. Ser.* 543, 141–152. doi: 10.3354/meps11554

Filbee-Dexter, K., and Scheibling, R. E. (2014). Sea urchin barrens as alternative stable states of collapsed kelp ecosystems. *Mar. Ecol. Prog. Ser.* 495, 1–25. doi: 10.3354/meps10573

Filbee-Dexter, K., and Wernberg, T. (2018). Rise of turfs: a new battlefront for globally declining kelp forests. *Bioscience* 68, 64–76. doi: 10.1093/biosci/bix147

Finn, P., Udy, N. S., Baltais, S. J., Price, K., and Coles, L. (2010). Assessing the quality of seagrass data collected by community volunteers in moreton bay marine park, Australia. *Environ. Conserv.* 37, 83–89. doi: 10.1017/S0376892910000251

Foden, J., and Brazier, D. P. (2007). Angiosperms (seagrass) within the EU water framework directive: a UK perspective. *Mar. Pollut. Bull.* 55, 181–195. doi: 10.1016/j.marpolbul.2006.08.021

Fortes, M. D., Ooi, J. L. S., Tan, Y. M., Prathep, A., Bujang, J. S., and Yaakub, S. M. (2018). Seagrass in Southeast Asia: a review of status and knowledge gaps, and a road map for conservation. *Bot. Marina* 61, 269–288. doi: 10.1515/bot-2018-0008

Foster, M. S., and Schiel, D. R. (2010). Loss of predators and the collapse of southern California kelp forests (?): Alternatives, explanations and generalizations. *J. Exp. Mar. Biol. Ecol.* 393, 59–70. doi: 10.1016/j.jembe.2010.07.002

Fourqurean, J. W., Duarte, C. M., Kennedy, H., Marbà, N., Holmer, M., Mateo, M. A., et al. (2012). Seagrass ecosystems as a globally significant carbon stock. *Nat. Geosci.* 5, 1–5. doi: 10.1038/ngeo1477

Fowles, A. E., Stuart-Smith, R. D., Stuart-Smith, J. F., Hill, N. A., Kirkpatrick, J. B., and Edgar, G. J. (2018). Effects of urbanisation on macroalgae and sessile invertebrates in southeast Australian estuaries. *Estuar. Coast. Shelf.* 205, 30–39. doi: 10.1016/j.ecss.2018.02.010

Frans, V. F., and Auge, A. A. (2016). Use of local ecological knowledge to investigate endangered baleen whale recovery in the Falkland Islands. *Biol. Conserv.* 202, 127–137. doi: 10.1016/j.biocon.2016.08.017

Fraser, C. I., Morrison, A. K., Hogg, A. M., Macaya, E. C., van Sebille, E., Ryan, P. G., et al. (2018). Antarctica's ecological isolation will be broken by storm-driven dispersal and warming. *Nat. Clim. Chang.* 8, 704–708. doi: 10.1038/s41558-018-0209-7

Fuentes, M., Delean, S., Grayson, J., Lavender, S., Logan, M., and Marsh, H. (2016). Spatial and temporal variation in the effects of climatic variables on dugong calf production. *PLoS ONE* 11:e0155675. doi: 10.1371/journal.pone.0155675

Fulton, C. J., Depczynski, M., Holmes, T. H., Noble, M. M., Radford, B., Wernberg, T., et al. (2014). Sea temperature shapes seasonal fluctuations in seaweed biomass within the Ningaloo coral reef ecosystem. *Limnol. Oceanogr.* 59, 156–166. doi: 10.4319/lo.2014.59.1.0156

Gattuso, J.-P., Gentili, B., Duarte, C. M., Kleypas, J. A., Middelburg, J. J., and Antoine, D. (2006). Light availability in the coastal ocean: impact on the distribution of benthic photosynthetic organisms and contribution to primary production. *Biogeosci. Discuss.* 3, 895–959. doi: 10.5194/bgd-3-895-2006

Gavio, B., and Santos-Martinez, A. (2018). Floating Sargassum in Serranilla Bank, Caribbean Colombia, may jeopardize the race to the ocean of baby sea turtles. *Acta Biol. Colomb.* 23, 311–313. doi: 10.15446/abc.v23n3.68113

Gedan, K. B., Kirwan, M. L., Wolanski, E., Barbier, E. B., and Silliman, B. R. (2011). The present and future role of coastal wetland vegetation in protecting shorelines: answering recent challenges to the paradigm. *Clim. Change* 106, 7–29. doi: 10.1007/s10584-010-0003-7

Geider, R. J., Delucia, E. H., Falkowski, P. G., Finzi, A. C., Grime, J. P., Grace, J., et al. (2001). Primary productivity of planet earth: biological determinants and physical constraints in terrestrial and aquatic habitats. *Glob. Chang. Biol.* 7, 849–882. doi: 10.1046/j.1365-2486.2001.00448.x

Gianni, F., Bartolini, F., Pey, A., Laurent, M., Martins, G. M., Airoldi, L., et al. (2017). Threats to large brown algal forests in temperate seas: the overlooked role of native herbivorous fish. *Sci. Rep.* 7:6012. doi: 10.1038/s41598-017-06394-7

Goodwin, K. D., Muller-Karger, F. E., Djurhuus, A., Allen, L. Z., Allen, A. E., McCrow, J. P., et al. (2019). "Molecular Approaches for an Operational Marine Biodiversity Observation Network," in *World Seas: an Environmental Evaluation,* ed C. Shepherd (Amsterdam: Elsevier), 613–631. doi: 10.1016/B978-0-12-805052-1.00032-2

Gower, J. F., and King, S. A. (2011). Distribution of floating Sargassum in the Gulf of Mexico and the Atlantic Ocean mapped using MERIS. *Int. J. Remote Sens.* 32, 1917–1929. doi: 10.1080/01431161003639660

Graham, M. H., Kinlan, B. P., Druehl, L. D., Garske, L. E., and Banks, S. (2007). Deep-water kelp refugia as potential hotspots of tropical marine diversity and productivity. *Proc. Natl. Acad. Sci. U.S.A.* 104, 16576–16580. doi: 10.1073/pnas.0704778104

Green, E. P., and Short, F. T. (2003). *World Atlas of Seagrasses*. University of California Press. Available online at: http://books.google.com/books?hl=en&lr=&id=dHV0NA3m2AIC&oi=fnd&pg=PA1&dq=world+atlas+of+seagrasses+short&ots=wxBQHQxIJP&sig=U3kliAAUH0Jf4H-yDtfsLZ5PLzw

Greening, H., Janicki, A., and Sherwood, E. T. (2018). "Seagrass recovery in tampa Bay, Florida (USA)," in *The Wetland Book: II: Distribution, Description, and Conservation* (Dordrecht: Springer), 495–506. doi: 10.1007/978-94-007-4001-3_269

Gregow, H., Laaksonen, A., and Alper, M. E. (2017). Increasing large scale windstorm damage in Western, Central and Northern European forests, 1951–2010. *Sci. Rep.* 7:46397. doi: 10.1038/srep46397

Greve, T. M., Borum, J., and Pedersen, O. (2003). Meristematic oxygen variability in eelgrass (*Zostera marina*). *Limnol. Oceanogr.* 48, 210–216. doi: 10.4319/lo.2003.48.1.0210

Hamaguchi, M., Shimabukuro, H., Hori, M., Yoshida, G., Terada, T., and Miyajima, T. (2018). Quantitative real-time polymerase chain reaction (PCR) and droplet digital PCR duplex assays for detecting Zostera marina DNA in coastal sediments. *Limnol. Oceanogr.* 16, 253–264. doi: 10.1002/lom3.10242

Hamilton, J., and Konar, B. (2007). Implications of substrate complexity and kelp variability for south-central Alaskan nearshore fish communities. *Fish B-Noaa* 105, 189–196.

Hammer, K. J., Borum, J., Hasler-Sheetal, H., Shields, E. C., Sand-Jensen, K., and Moore, K. A. (2018). High temperatures cause reduced growth, plant death and metabolic changes in eelgrass Zostera marina. *Mar. Ecol. Prog. Ser.* 604, 121–132. doi: 10.3354/meps12740

Harvell, C. D., Mitchell, C. E., Ward, J. R., Altizer, S., Dobson, A. P., Ostfeld, R. S., et al. (2002). Climate warming and disease risks for terrestrial and marine biota. *Science* 296, 2158–2162. doi: 10.1126/science.1063699

Hashim, M., Ito, S., Numata, S., Hosaka, T., Hossain, M. S., Misbari, S., et al. (2017). Using fisher knowledge, mapping population, habitat suitability and risk for the conservation of dugongs in Johor Straits of Malaysia. *Marine Policy* 78, 18–25. doi: 10.1016/j.marpol.2017.01.002

Heck, K., Hays, G., and Orth, R. (2003). Critical evaluation of the nursery role hypothesis for seagrass meadows. *Mar. Ecol. Prog. Ser.* 253, 123–136. doi: 10.3354/meps253123

Heidelbaugh, W. S., and Nelson, W. G. (1996). A power analysis of methods for assessment of change in seagrass cover. *Aquat. Bot.* 53, 227–243. doi: 10.1016/0304-3770(95)01000-9

Hieronymi, M., Müller, D., and Doerffer, R. (2017). The OLCI neural network swarm (ONNS): a bio-geo-optical algorithm for open ocean and coastal waters. *Front. Marine Sci.* 4:138. doi: 10.3389/fmars.2017.00140

Hill, R., Bellgrove, A., Macreadie, P., Petrou, K., Beardall, J., Steven, A., et al. (2015). Can macroalgae contribute to blue carbon? *An Australian perspective. Limnology and Oceanography* 60, 1689–1706. doi: 10.1002/lno.10128

Hossain, M., Rogers, K., and Saintilan, N. (2010). Variation in seagrass biomass estimates in low and high density settings: implications for the selection of sample size. *Environ. Indicat.* 5, 17–27.

Hossain, M. S., Bujang, J. S., Zakaria, M. H., and Hashim, M. (2015). The application of remote sensing to seagrass ecosystems: an overview and future research prospects. *International Journal of …* 36, 61–113. doi: 10.1080/01431161.2014.990649

Howard, J., Sutton-Grier, A., Herr, D., Kleypas, J., Landis, E., Mcleod, E., et al. (2017). Clarifying the role of coastal and marine systems in climate mitigation. *Front. Ecol. Environ.* 15, 42–50. doi: 10.1002/fee.1451

Hu, C., Feng, L., Hardy, R. F., and Hochberg, E. J. (2015). Spectral and spatial requirements of remote measurements of pelagic *Sargassum macroalgae*. *Remote Sens. Environ.* 167, 229–246. doi: 10.1016/j.rse.2015.05.022

Hu, C., Murch, B., Barnes, B. B., Wang, M., Maréchal, J.-P., Franks, J., et al. (2016). Sargassum watch warns of incoming seaweed. *EOS* 97, 10–15. doi: 10.1029/2016EO058355

Hu, L., Hu, C., and Ming-Xia, H. E. (2017). Remote estimation of biomass of Ulva prolifera macroalgae in the Yellow Sea. *Remote Sens. Environ.* 192, 217–227. doi: 10.1016/j.rse.2017.01.037

Hu, P., Liu, Y., Hou, Y., and Yin, Y. (2018). An early forecasting method for the drift path of green tides: a case study in the Yellow Sea, China. *Int. J. Appl. Earth Observ. Geoinform.* 71, 121–131. doi: 10.1016/j.jag.2018.05.001

Huffard, C. L., von Thun, S., Sherman, A. D., Sealey, K., and Smith, K. L. (2014). Pelagic Sargassum community change over a 40-year period: temporal and spatial variability. *Mar. Biol.* 161, 2735–2751. doi: 10.1007/s00227-014-2539-y

Hughes, A. R., Williams, S. L., Duarte, C. M., Heck, K. L., and Waycott, M. (2009). Associations of concern: declining seagrasses and threatened dependent species. *Front. Ecol. Environ.* 7, 242–246. doi: 10.1890/080041

Hughes, B. B., Eby, R., Van Dyke, E., Tinker, M. T., Marks, C. I., Johnson, K. S., et al. (2013). Recovery of a top predator mediates negative eutrophic effects on seagrass. *Proc. Natl. Acad. Sci. U.S.A.* 110, 15313–15318. doi: 10.1073/pnas.1302805110

Izaguirre, C., Méndez, F. J., Menéndez, M., and Losada, I. J. (2011). Global extreme wave height variability based on satellite data. *Geophys. Res. Lett.* 38:L10607. doi: 10.1029/2011GL047302

Jackson, E. L., Rees, S. E., Wilding, C., and Attrill, M. J. (2015). Use of a seagrass residency index to apportion commercial fishery landing values and recreation fisheries expenditure to seagrass habitat service. *Conserv. Biol.* 29, 899–909. doi: 10.1111/cobi.12436

Jackson, J. B. C. (1997). Reefs since Columbus. *Coral Reefs* 16, 23–32. doi: 10.1007/s003380050238

Jayathilake, D. R. M., and Costello, M. J. (2018). A modelled global distribution of the seagrass biome. *Biol. Conserv.* 226, 120–126. doi: 10.1016/j.biocon.2018.07.009

Johannes, R. E., Freeman, M. M. R., and Hamilton, R. J. (2000). Ignore fishers' knowledge and miss the boat. *Fish Fish.* 1, 257–271. doi: 10.1046/j.1467-2979.2000.00019.x

Johansson, M. L., Alberto, F., Reed, D. C., Raimondi, P. T., Coelho, N. C., Young, M. A., et al. (2015). Seascape drivers of M acrocystis pyrifera population genetic structure in the northeast P acific. *Mol. Ecol.* 24, 4866–4885. doi: 10.1111/mec.13371

Johnson, C. R., Banks, S. C., Barrett, N. S., Cazassus, F., Dunstan, P. K., Edgar, G. J., et al. (2011). Climate change cascades: Shifts in oceanography, species' ranges and subtidal marine community dynamics in eastern Tasmania. *J. Exp. Mar. Biol. Ecol.* 400, 17–32. doi: 10.1016/j.jembe.2011.02.032

Johnson, C. R., Koch, M. S., Pedersen, O., and Madden, C. J. (2018). Hypersalinity as a trigger of seagrass (*Thalassia testudinum*) die-off events in Florida Bay: evidence based on shoot meristem O 2 and H 2 S dynamics. *J. Exp. Mar. Biol. Ecol.* 504, 47–52. doi: 10.1016/j.jembe.2018.03.007

Johnson, C. R., Ling, S. D., and Strain, E. M. A. (2013). "Is "barrens" habitat good for sea urchins?," in *Echinoderms in a Changing World* (Boca Raton, FL), 254–255.

Jones, B. L., Unsworth, R. K. F., McKenzie, L. J., Yoshida, R. L., and Cullen-Unsworth, L. C. (2017). Crowdsourcing conservation: the role of citizen science in securing a future for seagrass. *Mar. Pollut. Bull.* 134, 210–215. doi: 10.1016/j.marpolbul.2017.11.005

Kaartvedt, S., Rostad, A., Klevjer, T. A., and Staby, A. (2009). Use of bottom-mounted echo sounders in exploring behavior of mesopelagic fishes. *Mar. Ecol. Prog. Ser.* 395, 109–118. doi: 10.3354/meps08174

Kaldy, J. E. (2014). Effect of temperature and nutrient manipulations on eelgrass Zostera marina L. *from the Pacific Northwest, USA. J. Exp. Mar. Biol. Ecol.* 453, 108–115. doi: 10.1016/j.jembe.2013.12.020

Kavanaugh, M. T., Oliver, M. J., Chavez, F. P., Letelier, R. M., Muller-Karger, F. E., and Doney, S. C. (2016). Seascapes as a new vernacular for pelagic ocean monitoring, management and conservation. *ICES J. Marine Sci.* 73, 1839–1850. doi: 10.1093/icesjms/fsw086

Kendrick, G., Aylward, M., Hegge, B., Cambridge, M., Hillman, K., Wyllie, A., et al. (2002). Changes in seagrass coverage in Cockburn Sound, Western Australia between 1967 and 1999. *Aquat. Bot.* 73, 75–87. doi: 10.1016/S0304-3770(02)00005-0

Kennedy, H., Beggins, J., Duarte, C. M., Fourqurean, J. W., Holmer, M., Marbà, N., et al. (2010). Seagrass sediments as a global carbon sink: Isotopic constraints. *Global Biogeochem. Cycles* 24:GB4026. doi: 10.1029/2010GB003848

Kerrylee, R., Macreadie, P., Kelleway, J., and Saintilan, N. (2018). Blue carbon in coastal landscapes: a spatial framework for assessment of stocks and additionality. *Sustainability Science* 14:453–467. doi: 10.1007/s11625-018-0575-0

Kimura, S., Cox, G., Carroll, J., Pengilley, S., and Harmer, A. (2012). *Going the Distance: Use of Diver Propulsion Units, Underwater Acoustic Navigation, and Three-Way Wireless Communication to Survey Kelp Forest Habitats*. American Academy of Underwater Sciences.

Kindeberg, T., Ørberg, S. B., Röhr, M. E., Holmer, M., and Krause-Jensen, D. (2018). Sediment stocks of carbon, nitrogen, and phosphorus in Danish eelgrass meadows. *Front. Mar. Sci.* 5:474. doi: 10.3389/fmars.2018.00474

King, S. A., and Lester, J. N. (1995). The value of salt marsh as a sea defence. *Mar. Pollut. Bull.* 30, 180–189. doi: 10.1016/0025-326X(94)00173-7

Kingsford, M. J., and Choat, J. H. (1985). The fauna associated with drift algae captured with a plankton-mesh purse seine net1. *Limnol. Oceanogr.* 30, 618–630. doi: 10.4319/lo.1985.30.3.0618

Knowlton, N. (1993). Sibling species in the sea. *Annu. Rev. Ecol. Syst*. Available online at: http://www.jstor.org/stable/2097177

Knudby, A., and Nordlund, L. (2011). Remote sensing of seagrasses in a patchy multi-species environment. *Int. J. Remote Sens.* 32, 2227–2244. doi: 10.1080/01431161003692057

Koch, M. S., Schopmeyer, S. A., Kyhn-Hansen, C., Madden, C. J., and Peters, J. S. (2007). Tropical seagrass species tolerance to hypersalinity stress. *Aquat. Bot.* 86, 14–24. doi: 10.1016/j.aquabot.2006.08.003

Konar, B., Edwards, M. S., and Estes, J. A. (2014). Biological interactions maintain the boundaries between kelp forests and urchin barrens in the Aleutian Archipelago. *Hydrobiologia* 724, 91–107. doi: 10.1007/s10750-013-1727-y

Konar, B., and Iken, K. (2018). The use of unmanned aerial vehicle imagery in intertidal monitoring. *Deep-Sea Res.* 147, 79–86. doi: 10.1016/j.dsr2.2017.04.010

Konar, B., Iken, K., Cruz-Motta, J. J., Benedetti-Cecchi, L., Knowlton, A., Pohle, G., et al. (2010). Current patterns of macroalgal diversity and biomass in northern hemisphere rocky shores. *PLoS ONE* 5. doi: 10.1371/journal.pone.0013195

Kortsch, S., Primicerio, R., Beuchel, F., Renaud, P. E., Rodrigues, J., Lønne, O. J., et al. (2012). Climate-driven regime shifts in Arctic marine benthos. *Proc. Natl. Acad. Sci. U.S.A.* 109, 14052–14057. doi: 10.1073/pnas.1207509109

Krause-Jensen, D., and Duarte, C. M. (2014). Expansion of vegetated coastal ecosystems in the future Arctic. *Front. Mar. Sci.* 1:77. doi: 10.3389/fmars.2014.00077

Krause-Jensen, D., and Duarte, C. M. (2016). Substantial role of macroalgae in marine carbon sequestration. *Nat. Geosci.* 9, 737–738. doi: 10.1038/ngeo2790

Krause-Jensen, D., Greve, T. M., and Nielsen, K. (2005). Eelgrass as a bioindicator under the european water framework directive. *Water Resour. Manage* 19, 63–75. doi: 10.1007/s11269-005-0293-0

Krause-Jensen, D., Marbà, N., Olesen, B., Sejr, M. K., Christensen, P. B., Rodrigues, J., et al. (2012). Seasonal sea ice cover as principal driver of spatial and temporal variation in depth extension and annual production of kelp in Greenland. *Glob. Chang. Biol.* 18, 2981–2994. doi: 10.1111/j.1365-2486.2012.02765.x

Krause-Jensen, D., Serrano, O., Apostolaki, E. T., Gregory, D. J., and Duarte, C. M. (2018). Seagrass sedimentary deposits as security vaults and time capsules of the human past. *Ambio* 48, 325–335. doi: 10.1007/s13280-018-1083-2

Kritzer, J. P., DeLucia, M.-B., Greene, E., Shumway, C., Topolski, M. F., Thomas-Blate, J., et al. (2016). The importance of benthic habitats for coastal fisheries. *Bioscience* 66, 274–284. doi: 10.1093/biosci/biw014

Krumhansl, K. A., Okamoto, D. K., Rassweiler, A., Novak, M., Bolton, J. J., Cavanaugh, K. C., et al. (2016). Global patterns of kelp forest change over the past half-century. *Proc. Natl. Acad. Sci. U.S.A.* 113, 13785–13790. doi: 10.1073/pnas.1606102113

Krumhansl, K. A., and Scheibling, R. E. (2012). Production and fate of kelp detritus. *Mar. Ecol. Prog. Ser.* 467, 281–302. doi: 10.3354/meps09940

Lamb, J. B., van de Water, J. A. J. M., Bourne, D. G., Altier, C., Hein, M. Y., Fiorenza, E. A., et al. (2017). Seagrass ecosystems reduce exposure to bacterial pathogens of humans, fishes, and invertebrates. *Science* 355, 731–733. doi: 10.1126/science.aal1956

Lamit, N., Tanaka, Y., Majid, H., and Link, G. B. (2017). Seagrass diversity in Brunei Darussalam: first records of three species. *Sci. Bruneiana* 16, 48–52.

Langlois, T. C. P. (2006). Baited underwater video for assessing reef fish populations in marine reserves. *SPC Fish. Newslett.* 118:53.

Laruelle, G. G., Landschützer, P., Gruber, N., Tison, J. L., Delille, B., and Regnier, P. (2017). Global high-resolution monthly pCO2 climatology for the coastal ocean derived from neural network interpolation. *Biogeosciences* 14, 4545–4561. doi: 10.5194/bg-14-4545-2017

Lee Long, W. J., McKenzie, L. J., Rasheed, M. A., and Coles, R. G. (1996). "Monitoring Seagrasses in Tropical Ports and Harbours," in *Seagrass Biology: Proceedings of an International Workshop, Rottnest Island, Western Australia 25-29 January, 1996*, eds J. Kuo, R. C. Phillips, D. I. Walker, and H. Kirkman (Perth, WA: Faculty of Sciences, The University of Western Australia), 345–350.

Lefcheck, J. S., Hughes, B. B., Johnson, A. J., Pfirrman, B. W., Rasher, D. B., Smyth, A. R., et al. (2019). Are coastal habitats important nurseries? A meta-analysis. *Conserv. Lett*. e12645. doi: 10.1111/conl.12645

Lindstrom, E., Gunn, J., Fischer, A., McCurdy, A., and Glover, L. K. (2012). *A Framework for Ocean Observing*. By the Task Team for an Integrated Framework for Sustained Ocean Observing. doi: 10.5270/OceanObs09-FOO

Ling, S. D., Johnson, C. R., Frusher, S. D., and Ridgway, K. R. (2009). Overfishing reduces resilience of kelp beds to climate-driven catastrophic phase shift. *Proc. Natl. Acad. Sci. U.S.A.* 106, 22341–22345. doi: 10.1073/pnas.0907529106

Ling, S. D., Mahon, I., Marzloff, M. P., Pizarro, O., Johnson, C. R., and Williams, S. B. (2016). Stereo-imaging AUV detects trends in sea urchin abundance on deep overgrazed reefs. *Limnol. Oceanogr.* 14, 293–304. doi: 10.1002/lom3.10089

Ling, S. D., Scheibling, R. E., Rassweiler, A., Johnson, C. R., Shears, N., Connell, S. D., et al. (2015). Global regime shift dynamics of catastrophic sea urchin overgrazing. *Philosoph. Transac. R. Soc. Biol. Sci.* 370:20130269. doi: 10.1098/rstb.2013.0269

Lourenco, C. R., Zardi, G. I., McQuaid, C. D., Serrao, E. A., Pearson, G. A., Jacinto, R., et al. (2016). Upwelling areas as climate change refugia for the distribution and genetic diversity of a marine macroalga. *J. Biogeogr.* 43, 1595–1607. doi: 10.1111/jbi.12744

Macreadie, P., Trevathan-Tackett, S., Skilbeck, C., Sanderman, J., Curlevski, N., Jacobsen, G., et al. (2015). Losses and recovery of organic carbon from a seagrass ecosystem following disturbance. *Proc. R. Soc. London B* 282, 1–6. doi: 10.1098/rspb.2015.1537

Macreadie, P. I., Jarvis, J., Trevathan-Tackett, S. M., and Bellgrove, A. (2017). "Seagrasses and Macroalgae: Importance, Vulnerability and Impacts," in *Climate Change Impacts on Fisheries and Aquaculture: A Global Analysis* (Wiley-Blackwell), 729–770. doi: 10.1002/9781119154051.ch22

Madin, J. S., Baird, A. H., Dornelas, M., and Connolly, S. R. (2014). Mechanical vulnerability explains size-dependent mortality of reef corals. *Ecol. Lett.* 17, 1008–1015. doi: 10.1111/ele.12306

Mansfield, K. L., and Putman, N. F. (2013). Oceanic habits and habitats. *Biol. Sea Turtles* 3, 189–211. doi: 10.1201/b13895-9

Mansfield, K. L., Wyneken, J., Porter, W. P., and Luo, J. (2014). First satellite tracks of neonate sea turtles redefine the 'lost years' oceanic niche. *Proce. R. Soc. Lond. B* 281:20133039. doi: 10.1098/rspb.2013.3039

Marbà, N., Arias Ortiz, A., Masqué, P., Kendrick, G. A., Mazarrasa, I., Bastyan, G. R., et al. (2015). Impact of seagrass loss and subsequent revegetation on carbon sequestration and stocks. *J. Ecol.* 103, 296–302. doi: 10.1111/1365-2745.12370

Marbà, N., Krause-Jensen, D., Alcoverro, T., Birk, S., Pedersen, A., Neto, J. M., et al. (2013). Diversity of European seagrass indicators: patterns within and across regions. *Hydrobiologia* 704, 265–278. doi: 10.1007/s10750-012-1403-7

Markiewicz, A., and Patrick, I. (2015). *Developing Monitoring and Evaluation Frameworks*. Thousand Oaks, CA: SAGE Publications.

Marsh, H., De'ath, G., Gribble, N., and Lane, B. (2005). Historical marine population estimates: triggers or targets for conservation? The dugongcase study. *Ecol. Appl.* 15, 481–492. doi: 10.1890/04-0673

Marsh, H., Grech, A., and McMahon, K. (2018). "Dugongs: Seagrass Community Specialists.," in *Seagrasses of Australia* (Cham: Springer). doi: 10.1007/978-3-319-71354-0_19

Marsh, H., O'Shea, T., and Reynolds, J. (2011). *Ecology and Conservation of the Sirenia: Dugongs and Manatees. No. 18*. Cambridge University Press. doi: 10.1017/CBO9781139013277

Martinez, B., Wernberg, T., Radford, B., Thomsen, M. S., Russell, B. D., Connell, S. D., et al. (2018). Distribution models predict large contractions in habitat-forming seaweeds in response to ocean warming. *Divers. Distribut.* 24, 1350–1366. doi: 10.1111/ddi.12767

Marzinelli, E. M., Campbell, A. H., Valdes, E. Z., Verges, A., Nielsen, S., Wernberg, T., et al. (2015a). Continental-scale variation in seaweed host-associated bacterial communities is a function of host condition, not geography. *Environ. Microbiol.* 17, 4078–4088. doi: 10.1111/1462-2920.12972

Marzinelli, E. M., Williams, S. B., Babcock, R. C., Barrett, N. S., Johnson, C. R., Jordan, A., et al. (2015b). Large-scale geographic variation in distribution and abundance of australian deep-water kelp forests. *PLoS ONE* 10:e0118390. doi: 10.1371/journal.pone.0118390

McCarthy, M. J., Radabaugh, K. R., Moyer, R. P., and Muller-Karger, F. E. (2018). Enabling efficient, large-scale high-spatial resolution wetland mapping using satellites. *Remote Sens. Environ.* 208, 189–201. doi: 10.1016/j.rse.2018.02.021

McKenzie, L., Collier, C., Langlois, L., Yoshida, R., Smith, N., and Waycott, M. (2017). *Marine Monitoring Program*. Annual Report for Inshore Seagrass Monitoring: 2015 to 2016, Great Barrier Reef Marine Park Authority, Townsville.

McKenzie, L. J., Long, L., and Marina, R. C. B. (2000). Seagrass-watch: community based monitoring of seagrass resources. *Biol. Mar. Medit.* 7, 393–396.

Mcleod, E., Chmura, G. L., Bouillon, S., Salm, R., Björk, M., Duarte, C. M., et al. (2011). A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO 2. *Front. Ecol. Environ.* 9, 552–560. doi: 10.1890/110004

MEA (2005). *Millennium Ecosystem Assessment. Ecosystems and Human Well-being: Synthesis.* Washington, DC: Island Press.

Mieszkowska, N., Kendall, M., Hawkins, S., Leaper, R., Williamson, P., Hardman-Mountford, N., et al. (2006). Changes in the range of some common rocky shore species in Britain–a response to climate change? *Hydrobiologia* 555, 241–251. doi: 10.1007/s10750-005-1120-6

Mieszkowska, N., Sugden, H., Firth, L. B., and Hawkins, S. J. (2014). The role of sustained observations in tracking impacts of environmental change on marine biodiversity and ecosystems. *Phil. Trans. R. Soc. A* 372 :20130339. doi: 10.1098/rsta.2013.0339

Miloslavich, P., Bax, N. J., Simmons, S. E., Klein, E., Appeltans, W., Aburto-Oropeza, O., et al. (2018). Essential ocean variables for global sustained observations of biodiversity and ecosystem changes. *Glob. Chang. Biol.* 105, 10456–10418. doi: 10.1111/gcb.14108

Moller, H., Berkes, F., Lyver, P. O., and Kislalioglu, M. (2004). Combining science and traditional ecological knowledge: monitoring populations for co-management. *Ecol. Soc.* 9:2. doi: 10.5751/ES-00675-090302

Moore, A. M., Ambo-Rappe, R., and Ali, Y. (2017). "The Lost Princess (putri duyung)" of the small islands: dugongs around sulawesi in the anthropocene. *Front. Mar. Sci.* 4:284. doi: 10.3389/fmars.2017.00284

Moore, K. A., and Jarvis, J. C. (2008). Environmental factors affecting recent summertime eelgrass diebacks in the lower chesapeake bay: implications for long-term persistence. *J. Coastal Res.* 55, 135–147. doi: 10.2112/SI55-014

Muller-Karger, F. E., Miloslavich, P., Bax, N. J., Simmons, S., Costello, M. J., Sousa-Pinto, I., et al. (2018). Advancing marine biological observations and data requirements of the complementary essential ocean variables (EOVs) and essential biodiversity variables (EBVs) frameworks. *Front. Marine Sci.* 5:e0141039–e0141015. doi: 10.3389/fmars.2018.00211

Murfitt, S. L., Allan, B. M., Bellgrove, A., Rattray, A., Young, M. A., and Ierodiaconou, D. (2017). Applications of unmanned aerial vehicles in intertidal reef monitoring. *Sci. Rep.* 7:10259. doi: 10.1038/s41598-017-10818-9

Neckles, H. A., Kopp, B. S., Peterson, B. J., and Pooler, P. S. (2012). Integrating scales of seagrass monitoring to meet conservation needs. *Estuar. Coasts* 35, 23–46. doi: 10.1007/s12237-011-9410-x

Neiva, J., Assis, J., Coelho, N. C., Fernandes, F., Pearson, G. A., and Serrao, E. A. (2015). Genes left behind: climate change threatens cryptic genetic diversity in the canopy-forming seaweed bifurcaria bifurcata. *PLoS ONE* 10:e0131530. doi: 10.1371/journal.pone.0131530

Neiva, J., Serrão, E. A., Anderson, L., Raimondi, P. T., Martins, N., Gouveia, L., et al. (2017). Cryptic diversity, geographical endemism and allopolyploidy in NE Pacific seaweeds. *BMC Evol. Biol.* 17:30. doi: 10.1186/s12862-017-0878-2

Nelleman, C. (2009). BLUE CARBON. The *Role* of *Healthy Oceans* in *Binding Carbon*. United Nations Environment Programme, 1–80.

Neori, A., Chopin, T., Troell, M., Buschmann, A. H., Kraemer, G. P., Halling, C., et al. (2004). Integrated aquaculture: rationale, evolution and state of the art emphasizing seaweed biofiltration in modern mariculture. *Aquaculture* 231, 361–391. doi: 10.1016/j.aquaculture.2003.11.015

Nicastro, K. R., Zardi, G. I., Teixeira, S., Neiva, J., Serrao, E. A., and Pearson, G. A. (2013). Shift happens: trailing edge contraction associated with recent warming trends threatens a distinct genetic lineage in the marine macroalga Fucus vesiculosus. *BMC Biol.* 11:6. doi: 10.1186/1741-7007-11-6

Nijland, W., Reshitnyk, L., and Rubidge, E. (2019). Satellite remote sensing of canopy-forming kelp on a complex coastline: a novel procedure using the Landsat image archive. *Remote Sens. Environ.* 220, 41–50. doi: 10.1016/j.rse.2018.10.032

NOAA (1996). *Magnuson-Stevens Fishery Conservation and Management Act, as Amended Through Oct. 11, 1996.* NOAA Tech. Mem. NMFS-F/SPO-23. 121 p.

Norderhaug, K. M., Gundersen, H., Pedersen, A., Moy, F., Green, N., Walday, M. G., et al. (2015). Effects of climate and eutrophication on the diversity of hard bottom communities on the Skagerrak coast 1990-2010. *Mar. Ecol. Prog. Ser.* 530, 29–46. doi: 10.3354/meps11306

Nordlund, L., Unsworth, R. K. F., Gullström, M., and Cullen-Unsworth, L. C. (2018). Global significance of seagrass fishery activity. *Fish Fish.* 19, 399–412. doi: 10.1111/faf.12259

Nordlund, L. M., Koch, E. W., Barbier, E. B., and Creed, J. C. (2016). Seagrass ecosystem services and their variability across genera and geographical regions. *PLoS ONE* 11:e0163091–e0163023. doi: 10.1371/journal.pone.0163091

O'Brien, J. M., Scheibling, R. E., and Krumhansl, K. A. (2015). Positive feedback between large-scale disturbance and density-dependent grazing decreases resilience of a kelp bed ecosystem. *Mar. Ecol. Prog. Ser.* 522, 1–13. doi: 10.3354/meps11193

Oliver, E. C. J., Donat, M. G., Burrows, M. T., Moore, P. J., Smale, D. A., Alexander, L. V., et al. (2018). Longer and more frequent marine heatwaves over the past century. *Nat. Commun.* 9:1324. doi: 10.1038/s41467-018-03732-9

Olsen, J. L., Stam, W. T., Coyer, J. A., Reusch, T. B., Billingham, M., Boström, C., et al. (2004). North Atlantic phylogeography and large-scale population differentiation of the seagrass Zostera marina L. *Mol. Ecol.* 13, 1923–1941. doi: 10.1111/j.1365-294X.2004.02205.x

Orth, R., Carruthers, T., Dennison, W., Duarte, C., Fourqurean, J., Heck Jr., K., et al. (2006). A global crisis for seagrass ecosystems. *Bioscience* 56, 987–996. doi: 10.1641/0006-3568(2006)56<987:AGCFSE>2.0.CO;2

Orth, R., and Van Montfrans, J. (1984). Epiphyte-seagrass relationships with an emphasis on the role of micrograzing: a review. *Aquat. Bot.* 18, 43–69. doi: 10.1016/0304-3770(84)90080-9

Östman, Ö., Eklöf, J., Eriksson, B. K., Olsson, J., Moksnes, P.-O., and Bergström, U. (2016). Top-down control as important as eutrophication effects in North Atlantic coastal ecosystems. *J. Appl. Ecol.* 53, 1138–1147. doi: 10.1111/1365-2664.12654

Patrick, W. S., and Link, J. S. (2015). Myths that continue to impede progress in ecosystem-based fisheries management. *Fisheries* 40, 155–160. doi: 10.1080/03632415.2015.1024308

Pauly, D. (1995). Anecdotes and the shifting baseline syndrome of fisheries. *Trends Ecol. Evol.* 10:430. doi: 10.1016/S0169-5347(00)89171-5

Pawlowski, J., Christen, R., Lecroq, B., Bachar, D., Shahbazkia, H. R., Amaral-Zettler, L., et al. (2011). Eukaryotic richness in the abyss: insights from pyrotag sequencing. *PLoS ONE* 6:e18169. doi: 10.1371/journal.pone.0018169

Pendleton, L., Donato, D. C., Murray, B. C., Crooks, S., Jenkins, W. A., Sifleet, S., et al. (2012). Estimating global "blue carbon" emissions from conversion and degradation of vegetated coastal ecosystems. *PLoS ONE* 7:e43542. doi: 10.1371/journal.pone.0043542

Pereira, H. M., Ferrier, S., Walters, M., Geller, G. N., Jongman, R. H. G., Scholes, R. J., et al. (2013). Essential biodiversity variables. *Science* 339, 277–278. doi: 10.1126/science.1229931

Perry, C. J., and Dennison, W. C. (1999). Microbial nutrient cycling in seagrass sediment. *J. Aust. Geol. Geophys.* 17, 227–231.

Perry, D. S. T. (2018). Habitat connectivity of fish in temperate shallow-water seascapes. *Front. Mar. Sci.* 4:440. doi: 10.3389/fmars.2017.00440

Personnic, S., Boudouresque, C. F., Astruch, P., Ballesteros, E., Blouet, S., Bellan-Santini, D., et al. (2014). An ecosystem-based approach to assess the status of a Mediterranean ecosystem, the Posidonia oceanica seagrass meadow. *PLoS ONE* 9:e98994. doi: 10.1371/journal.pone.0098994

Polidoro, B. A., Carpenter, K. E., Collins, L., Duke, N. C., Ellison, A. M., Ellison, J. C., et al. (2010). The loss of species: mangrove extinction risk and geographic areas of global concern. *PLoS ONE* 5:e10095. doi: 10.1371/journal.pone.0010095

Powers, S. P., Hernandez, F. J., Condon, R. H., Drymon, J. M., and Free, C. M. (2013). Novel pathways for injury from offshore oil spills: direct, sublethal and indirect effects of the deepwater horizon oil spill on pelagic sargassum communities. *PLoS ONE* 8:e74802. doi: 10.1371/journal.pone.0074802

Putman, N. F., Abreu-Grobois, F. A., Iturbe-Darkistade, I., Putman, E. M., Richards, P. M., and Verley, P. (2015). Deepwater Horizon oil spill impacts on sea turtles could span the Atlantic. *Biol. Lett*. 11:20150596. doi: 10.1098/rsbl.2015.0596

Putman, N. F., Goni, G. J., Gramer, L. J., Hu, C., Johns, E. M., Trinanes, J., et al. (2018). Simulating transport pathways of pelagic Sargassum from the equatorial atlantic into the Caribbean Sea. *Prog. Oceanogr.* 165, 205–214. doi: 10.1016/j.pocean.2018.06.009

Putman, N. F., and Mansfield, K. L. (2015). Direct evidence of swimming demonstrates active dispersal in the sea turtle "lost years." *Curr. Biol.* 25, 1221–1227. doi: 10.1016/j.cub.2015.03.014

Putman, N. F., Verley, P., Shay, T. J., and Lohmann, K. J. (2012). Simulating transoceanic migrations of young loggerhead sea turtles: merging magnetic navigation behavior with an ocean circulation model. *J. Exp. Biol.* 215, 1863–1870. doi: 10.1242/jeb.067587

Qi, L., Hu, C., Wang, M., Shang, S., and Wilson, C. (2017). Floating algae blooms in the East China Sea. *Geophys. Res. Lett.* 44, 11,501–11,509. doi: 10.1002/2017GL075525

Rapport, D., Gaudet, C., Constanza, R., Epstein, R., and Levins, R. (1998). "Defining Ecosystem Health," in *Ecosystem Health: Principles and Practice*, eds D. Rapport, C. Gaudet, R. Constanza, R. Epstein, and R. Levins (Oxford: Blackwell Science), 18–33.

Rebours, C., Marinho-Soriano, E., Zertuche-Gonzalez, J. A., Hayashi, L., Vasquez, J. A., Kradolfer, P., et al. (2014). Seaweeds: an opportunity for wealth and sustainable livelihood for coastal communities. *J. Appl. Phycol.* 26, 1939–1951. doi: 10.1007/s10811-014-0304-8

Reef, R., Atwood, T. B., Samper-Villarreal, J., Adame, M. F., Sampayo, E. M., and Lovelock, C. E. (2017). Using eDNA to determine the source of organic carbon in seagrass meadows. *Limnol. Oceanogr.* 62, 1254–1265. doi: 10.1002/lno.10499

Reusch, T. B. H., Ehlers, A., Hämmerli, A., and Worm, B. (2005). Ecosystem recovery after climatic extremes enhanced by genotypic diversity. *Proc. Natl. Acad. Sci. U.S.A.* 102, 2826–2831. doi: 10.1073/pnas.0500008102

Rindi, L., Dal Bello, M., Dai, L., Gore, J., and Benedetti-Cecchi, L. (2017). Direct observation of increasing recovery length before collapse of a marine benthic ecosystem. *Nat. Ecol. Evol.* 1:0153. doi: 10.1038/s41559-017-0153

Robblee, M. B., Barber, T. R., Carlson Jr., P. R., Durako, M. J., Fourqurean, J. W., Muehlstein, L. K., et al. (1991). Mass mortality of the tropical seagrass *Thalassia testudinum* in Florida Bay (USA). *Mar Ecol Progr Seri.* 71, 297–299. doi: 10.3354/meps071297

Roca, G., Alcoverro, T., Krause-Jensen, D., Balsby, T. J. S., van Katwijk, M. M., Marba, N., et al. (2016). Response of seagrass indicators to shifts in environmental stressors: a global review and management synthesis. *Ecol. Indic.* 63, 310–323. doi: 10.1016/j.ecolind.2015.12.007

Röhr, M. E., Holmer, M., Baum, J. K., Björk, M., Chin, D., Chalifour, L., et al. (2018). Blue carbon storage capacity of temperate eelgrass (*Zostera marina*) meadows. *Glob. Biogeochem. Cycles* 32, 1457. doi: 10.1029/2018GB005941

Ruiz-Frau, A., Gelcich, S., Hendriks, I. E., Duarte, C. M., and Marba, N. (2017). Current state of seagrass ecosystem services: research and policy integration. *Ocean Coastal Manage.* 149, 107–115. doi: 10.1016/j.ocecoaman.2017.10.004

Rupprecht, F., Möller, I., Paul, M., Kudella, M., Spencer, T., Van Wesenbeeck, B. K., et al. (2017). Vegetation-wave interactions in salt marshes under storm surge conditions. *Ecol. Eng.* 100, 301–315. doi: 10.1016/j.ecoleng.2016.12.030

Schell, J., Goodwin, D., and Siuda, A. (2015). Recent sargassum inundation events in the caribbean: shipboard observations reveal dominance of a previously rare form. *Oceanography* 8, 8–10. doi: 10.5670/oceanog.2015.70

Schultz, S. T., Kruschel, C., Bakran-Petricioli, T., and Petricioli, D. (2015). Error, power, and blind sentinels: the statistics of seagrass monitoring. *PLoS ONE* 10:e0138378. doi: 10.1371/journal.pone.0138378

Seddon, S., Connolly, R. M., and Edyvane, K. S. (2000). Large-scale seagrass dieback in northern Spencer Gulf, South Australia. *Aquat. Bot.* 66, 297–310. doi: 10.1016/S0304-3770(99)00080-7

Setyawidati, N., Kaimuddin, A. H., Wati, I. P., Helmi, M., Widowati, I., Rossi, N., et al. (2018). Percentage cover, biomass, distribution, and potential habitat mapping of natural macroalgae, based on high-resolution satellite data and *in situ* monitoring, at Libukang Island, Malasoro Bay, Indonesia. *J. Appl. Phycol.* 30, 159–171. doi: 10.1007/s10811-017-1208-1

Short, F., and Burdick, D. (1996). Quantifying eelgrass habitat loss in relation to housing development and nitrogen loading in Waquoit Bay, Massachusetts. *Estuar. Coasts* 19, 730–739. doi: 10.2307/1352532

Short, F., Carruthers, T., Dennison, W., and Waycott, M. (2007). Global seagrass distribution and diversity: a bioregional model. *J. Exp. Mar. Biol. Ecol.* 350, 3–20. doi: 10.1016/j.jembe.2007.06.012

Short, F., McKenzie, L. J., Coles, R., Vidler, K., and Gaeckle, J. (2006). *SeagrassNet Manual for Scientific Monitoring of Seagrass Habitat, Worldwide Edition.* Durham, NH: The University of New Hampshire.

Short, F., and Neckles, H. (1999). The effects of global climate change on seagrasses. *Aquat. Bot.* 63, 169–196. doi: 10.1016/S0304-3770(98)00117-X

Short, F. T., Coles, R., Fortes, M. D., Victor, S., Salik, M., Isnain, I., et al. (2014). Monitoring in the Western Pacific region shows evidence of seagrass decline in line with global trends. *Mar. Pollut. Bull.* 83, 408–416. doi: 10.1016/j.marpolbul.2014.03.036

Short, F. T., and Coles, R. G. (2001). *Global Seagrass Research Methods*, *33.* Available online at: http://www.worldcat.org/title/global-seagrass-research-methods/oclc/935245623

Short, F. T., Kosten, S., Morgan, P. A., Malone, S., and Moore, G. E. (2016). Impacts of climate change on submerged and emergent wetland plants. *Aquat. Bot.* 135, 3–17. doi: 10.1016/j.aquabot.2016.06.006

Short, F. T., Polidoro, B., Livingstone, S. R., Carpenter, K. E., Bandeira, S., Bujang, J. S., et al. (2011). Extinction risk assessment of the world's seagrass species. *Biol. Conserv.* 144, 1961–1971. doi: 10.1016/j.biocon.2011.04.010

Sievers, M., Brown, C. J., Tulloch, V. J., Pearson, R. M., Haig, J. A., Turschwell, M. P., et al. (2019). The role of vegetated coastal wetlands for marine megafauna conservation. *Trends Ecol. Evol*. doi: 10.1016/j.tree.2019.04.004. [Epub ahead of print].

Smith, T. M., York, P. H., Broitman, B. R., Thiel, M., Hays, G. C., van Sebille, E., et al. (2018). Rare long-distance dispersal of a marine angiosperm across the Pacific Ocean. *Glob. Ecol. Biogeogr.* 27, 487–496. doi: 10.1111/geb.12713

Steneck, R. S., and Johnson, C. R. (2013). "Kelp forests: dynamic patterns, processes and feedbacks," in *Marine Community Ecology*, eds M. Bertness, B. Silliman, and J. Stachowitz (Sunderland, MA: Sinaur Associates Inc.), 315–336.

Strain, E. M., Thomson, R. J., Micheli, F., Mancuso, F. P., and Airoldi, L. (2014). Identifying the interacting roles of stressors in driving the global loss of canopy-forming to mat-forming algae in marine ecosystems. *Glob. Change Biol.* 20, 3300–3312. doi: 10.1111/gcb.12619

Sullivan, B. K., Trevathan-Tackett, S. M., Neuhauser, S., and Govers, L. L. (2017). Review: Host-pathogen dynamics of seagrass diseases under future global change. *Mar. Pollut. Bull.* 134, 75–88. doi: 10.1016/j.marpolbul.2017.09.030

Sutton-Grier, A. E., Wowk, K., and Bamford, H. (2015). Future of our coasts: the potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems. *Environ. Sci. Policy* 51, 137–148. doi: 10.1016/j.envsci.2015.04.006

Taberlet, P., Coissac, E., Pompanon, F., Brochmann, C., and Willerslev, E. (2012). Towards next-generation biodiversity assessment using DNA metabarcoding. *Mol. Ecol.* 21, 2045–2050. doi: 10.1111/j.1365-294X.2012.05470.x

Tano, S., Eggertsen, M., Wikstrom, S. A., Berkstrom, C., Buriyo, A. S., and Hailing, C. (2016). Tropical seaweed beds are important habitats for mobile invertebrate epifauna. *Estuar. Coast. Shelf Sci.* 183, 1–12. doi: 10.1016/j.ecss.2016.10.010

Tano, S. A., Eggertsen, M., Wikstrom, S. A., Berkstrom, C., Buriyo, A. S., and Halling, C. (2017). Tropical seaweed beds as important habitats for juvenile fish. *Mar. Freshw. Res.* 68, 1921–1934. doi: 10.1071/MF16153

Teagle, H., Hawkins, S. J., Moore, P. J., and Smale, D. A. (2017). The role of kelp species as biogenic habitat formers in coastal marine ecosystems. *J. Exp. Mar. Biol. Ecol.* 492, 81–98. doi: 10.1016/j.jembe.2017.01.017

Tegner, M., and Dayton, P. K. (2000). Ecosystem effects of fishing in kelp forest communities. *ICES J. Mar. Sci.* 57, 579–589. doi: 10.1006/jmsc.2000.0715

Thibaut, T., Blanfuné, A., Boudouresque, C. F., Personnic, S., Ruitton, S., Ballesteros, E., et al. (2017). An ecosystem-based approach to assess the status of Mediterranean algae-dominated shallow rocky reefs. *Mar. Pollut. Bull.* 117, 311–329. doi: 10.1016/j.marpolbul.2017.01.029

Thibaut, T., Pinedo, S., Torras, X., and Ballesteros, E. (2005). Long-term decline of the populations of Fucales (Cystoseira spp. and Sargassum spp.) in the Alberes coast (France, North-western Mediterranean). *Mar. Pollut. Bull.* 50, 1472–1489. doi: 10.1016/j.marpolbul.2005.06.014

Thomsen, P. F., and Willerslev, E. (2015). Environmental DNA – An emerging tool in conservation for monitoring past and present biodiversity. *Biol. Conserv.* 183, 4–18. doi: 10.1016/j.biocon.2014.11.019

Titilola, S. (1990). *The Economics of Incorporating Indigenous Knowledge Systems Into Agricultural Development: A Model And Analytical Framework*. Studies in technology and social change (USA). Available online at: http://agris.fao.org/agris-search/search.do?recordID=US9404376

Tol, S. J., Jarvis, J. C., York, P. H., Grech, A., Congdon, B. C., and Coles, R. G. (2017). Long distance biotic dispersal of tropical seagrass seeds by marine mega-herbivores. *Sci. Rep.* 7:4458. doi: 10.1038/s41598-017-04421-1

Traganos, D., and Reinartz, P. (2018). Mapping Mediterranean seagrasses with Sentinel-2 imagery. *Mar. Pollut. Bull.* 134, 197–209. doi: 10.1016/j.marpolbul.2017.06.075

Travis, J., Coleman, F. C., Auster, P. J., Cury, P. M., Estes, J. A., Orensanz, J., et al. (2014). Integrating the invisible fabric of nature into fisheries management. *Proc. Natl. Acad. Sci. U.S.A.* 111, 581–584. doi: 10.1073/pnas.1305853111

Trevathan-Tackett, S. M., Kelleway, J., Macreadie, P. I., Beardall, J., Ralph, P., and Bellgrove, A. (2015). Comparison of marine macrophytes for their contributions to blue carbon sequestration. *Ecology* 96, 3043–3057. doi: 10.1890/15-0149.1

Uhl, F., Bartsch, I., and Oppelt, N. (2016). Submerged kelp detection with hyperspectral data. *Remote Sens.* 8:487. doi: 10.3390/rs8060487

Underwood, A. J. (1994). On beyond baci - sampling designs that might reliably detect environmental disturbances. *Ecol. Appl.* 4, 3–15. doi: 10.2307/1942110

UNEP (2006). *Marine and Coastal Ecosystems and Human Well-Being: A Synthesis Report Based on the Findings of the Millennium Ecosystem Assessment*. United Nations Environmental Programme.

Unsworth, R., Hinder, S. L., Bodger, O. G., and Cullen-Unsworth, L. C. (2014). Food supply depends on seagrass meadows in the coral triangle. *Environ. Res. Lett.* 9. doi: 10.1088/1748-9326/9/9/094005

Unsworth, R., Nordlund, L. M., and Cullen-Unsworth, L. C. (2018). Seagrass meadows support global fisheries production. *Conserv. Lett.* 8:e12566 doi: 10.1111/conl.12566

Unsworth, R., Rasheed, M. A., and Taylor, H. A. (2009). *Port of Townsville Long Term Seagrass Monitoring, October 2008.* DEEDI Publication PR09-4330. Cairns: QPIF.

Unsworth, R. K., Ambo-Rappe, R., Jones, B. L., La Nafie, Y. A., Irawan, A., Hernawan, U. E., et al. (2018). Indonesia's globally significant seagrass meadows are under widespread threat. *Sci. Total Environ.* 634, 279–286. doi: 10.1016/j.scitotenv.2018.03.315

Valero, M., Guillemin, M.-L., Destombe, C., Jacquemin, B., Gachon, C. M., Badis, Y., et al. (2017). Perspectives on domestication research for sustainable seaweed aquaculture. *Perspect. Phycol.* 33–46. doi: 10.1127/pip/2017/0066

Valiela, I., and Cole, M. (2002). Comparative evidence that salt marshes and mangroves may protect seagrass meadows from land-derived nitrogen loads. *Ecosystems* 5, 92–102. doi: 10.1007/s10021-001-0058-4

van Dijk, K., Bricker, E., van Tussenbroek, B. I., and Waycott, M. (2018). Range-wide population genetic structure of the Caribbean marine angiosperm *Thalassia testudinum*. *Ecol. Evol.* 8, 9478–9490. doi: 10.1002/ece3.4443

van Tussenbroek, B. I., Arana, H. A. H., Rodríguez-Martínez, R. E., Espinoza-Avalos, J., Canizales-Flores, H. M., González-Godoy, C. E., et al. (2017). Severe impacts of brown tides caused by Sargassum spp. on near-shore Caribbean seagrass communities. *Mar. Poll. Bull.* 122, 272–281. doi: 10.1016/j.marpolbul.2017.06.057

van Tussenbroek, B. I., Cortés, J., Collin, R., Fonseca, A. C., Gayle, P. M. H., Guzmán, H. M., et al. (2014). Caribbean-wide, long-term study of seagrass beds reveals local variations, shifts in community structure and occasional collapse. *PLoS ONE* 9:e90600. doi: 10.1371/journal.pone.0090600

Vásquez, J., Zuñiga, S., Tala, F., Piaget, N., Rodríguez, D., and Vega, J. M. A. (2014). Economic valuation of kelp forests in northern Chile: values of goods and services of the ecosystem. *J. Appl. Phycol.* 26, 1081–1088. doi: 10.1007/s10811-013-0173-6

Vassallo, P., Paoli, C., Rovere, A., Montefalcone, M., Morri, C., and Bianchi, C. N. (2013). The value of the seagrass *Posidonia oceanica*: a natural capital assessment. *Mar. Pollut. Bull.* 75, 157–167. doi: 10.1016/j.marpolbul.2013.07.044

Vergés, A., Steinberg, P. D., Hay, M. E., Poore, A. G. B., Campbell, A. H., Ballesteros, E., et al. (2014). The tropicalization of temperate marine ecosystems: climate-mediated changes in herbivory and community phase shifts. *Proc. R. Soc. B* 281:20140846. doi: 10.1098/rspb.2014.0846

Villon, S., Chaumont, M., Subsol, G., Villéger, S., Claverie, T., and Mouillot, D. (2016). "Coral reef fish detection and recognition in underwater videos by supervised machine learning: comparison between deep learning and HOG+SVM methods," in *Advanced Concepts for Intelligent Vision Systems*, eds J. Blanc-Talon, C. Distante, W. Philips, D. Popescu, and P. Scheunders (Springer International Publishing), 160–171. doi: 10.1007/978-3-319-48680-2_15

Vonk, J. A., Christianen, M. J. A., Stapel, J., and O'Brien, K. R. (2015). What lies beneath: why knowledge of belowground biomass dynamics is crucial to effective seagrass management. *Ecol. Indic.* 57, 259–267. doi: 10.1016/j.ecolind.2015.05.008

Walker, D. I., and McComb, A. J. (1990). Salinity response of the seagrass *Amphibolis antarctica* (Labill.) sonder et aschers.: an experimental validation of field results. *Aquat. Bot.* 36, 359–366. doi: 10.1016/0304-3770(90)90052-M

Wang, J., and Deng, Z. (2016). Modeling and prediction of oyster norovirus outbreaks along gulf of mexico coast. *Environ. Health Perspect.* 124, 627–633. doi: 10.1289/ehp.1509764

Wang, M., and Hu, C. (2016). Mapping and quantifying Sargassum distribution and coverage in the Central West Atlantic using MODIS observations. *Remote Sens. Environ.* 183, 350–367. doi: 10.1016/j.rse.2016.04.019

Wang, M., and Hu, C. (2018). On the continuity of quantifying floating algae of the Central West Atlantic between MODIS and VIIRS. *Int. J. Remote Sens.* 39, 3852–3869. doi: 10.1080/01431161.2018.1447161

Wang, M., Hu, C., Cannizzaro, J., English, D., Han, X., Naar, D., et al. (2018). Remote sensing of Sargassum biomass, nutrients, and pigments. *Geophys. Res. Lett.* 45, 12,359–12,367. doi: 10.1029/2018GL078858

Waycott, M., Duarte, C. M., Carruthers, T. J. B., Orth, R. J., Dennison, W. C., Olyarnik, S., et al. (2009). Accelerating loss of seagrasses across the globe threatens coastal ecosystems. *Proc. Natl. Acad. Sci. U.S.A.* 106, 12377–12381. doi: 10.1073/pnas.0905620106

Waycott, M., McKenzie, L., Mellors, J. E., Ellison, J. C., Sheaves, M. T., Collier, C., et al. (2011). "Vulnerability of mangroves, seagrasses and intertidal flats in the tropical Pacific to climate change," in *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change*, eds D. Johann, J. E. Johnson, and A. J. Hobday (Noumea: Secretariat of the Pacific Community), 297–368.

Wells, R. J., and Rooker, J. R. (2004). Spatial and temporal patterns of habitat use by fishes associated with Sargassum mats in the northwestern Gulf of Mexico. *Bull. Mar. Sci.* 74, 81–99.

Wernberg, T., Bennett, S., Babcock, R. C., de Bettignies, T., Cure, K., Depczynski, M., et al. (2016). Climate-driven regime shift of a temperate marine ecosystem. *Science* 353, 169–172. doi: 10.1126/science.aad8745

Wernberg, T., and Filbee-Dexter, K. (2018). Grazers extend blue carbon transfer by slowing sinking speeds of kelp detritus. *Sci. Rep.* 8:17180. doi: 10.1038/s41598-018-34721-z

Wernberg, T., and Filbee-Dexter, K. (2019). Missing the marine forest for the trees. *Mar. Ecol. Progr. Seri*. 612, p209–215. doi: 10.3354/meps12867

Wernberg, T., Krumhansl, K., Filbee-Dexter, K., and Pedersen, M. F. (2019). "Status and trends for the world's kelp forests," in *World Seas: an Environmental Evaluation*, ed C. Shepherd (Amsterdam: Elsevier), 57–78. doi: 10.1016/B978-0-12-805052-1.00003-6

Wernberg, T., Smale, D. A., and Thomsen, M. S. (2012). A decade of climate change experiments on marine organisms: procedures, patterns and problems. *Glob. Chang. Biol.* 18, 1491–1498. doi: 10.1111/j.1365-2486.2012.02656.x

Wieczorek, J., Bloom, D., Guralnick, R., Blum, S., Döring, M., Giovanni, R., et al. (2012). Darwin core: an evolving community-developed biodiversity data standard. *PLoS ONE* 7:e29715. doi: 10.1371/journal.pone.0029715

Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., Appleton, G., and Axton, M., Baak, A., et al. (2016). The FAIR Guiding Principles for scientific data management and stewardship. *Sci. Data* 3, 160018–160019. doi: 10.1038/sdata.2016.18

Wilmers, C. C., Estes, J. A., Edwards, M., Laidre, K. L., and Konar, B. (2012). Do trophic cascades affect the storage and flux of atmospheric carbon? An analysis of sea otters and kelp forests. *Front. Ecol. Environ.* 10, 409–415. doi: 10.1890/110176

Witherington, B., Hirama, S., and Hardy, R. (2012). Young sea turtles of the pelagic Sargassum-dominated drift community: Habitat use, population density, and threats. 63, 1–22. doi: 10.3354/meps09970

Woolf, D. K., Challenor, P. G., and Cotton, P. D. (2002). Variability and predictability of the North Atlantic wave climate. *J. Geophys. Res.* 107:3145. doi: 10.1029/2001JC001124

Wright, I. J., Reich, P. B., Westoby, M., Ackerly, D. D., Baruch, Z., Bongers, F., et al. (2004). The worldwide leaf economics spectrum. *Nature* 428, 821–827. doi: 10.1038/nature02403

Wyllie-Echeverria, S., Gunnarsson, K., Mateo, M. A., Borg, J. A., Renom, P., Kuo, J., et al. (2002). Protecting the seagrass biome: report from the traditional seagrass knowledge working group. *Bull. Mar. Sci.* 71, 1415–1416.

Yang, F., Long, L., Sun, X., Wu, H., Li, T., and Xiang, W. (2014). Optimization of medium using response surface methodology for lipid production by Scenedesmus sp. *Mar. Drugs* 12, 1245–1257. doi: 10.3390/md12031245

Yang, Y. F., Chai, Z. Y., Wang, Q., Chen, W. Z., He, Z. L., and Jiang, S. J. (2015). Cultivation of seaweed Gracilaria in Chinese coastal waters and its contribution to environmental improvements. *Algal Res.* 9, 236–244. doi: 10.1016/j.algal.2015.03.017

Zardi, G. I., Nicastro, K. R., Serrão, E. A., Jacinto, R., Monteiro, C. A., and Pearson, G. A. (2015). Closer to the rear edge: ecology and genetic diversity down the core-edge gradient of a marine macroalga. *Ecosphere* 6, 1–25. doi: 10.1890/ES14-00460.1

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frontiers in Marine Science

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An Integrated Data Analytics Platform

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An Integrated Science Data Analytics Platform is an environment that enables the confluence of resources for scientific investigation. It harmonizes data, tools and computational resources to enable the research community to focus on the investigation rather than spending time on security, data preparation, management, etc. OceanWorks is a NASA technology integration project to establish a cloud-based Integrated Ocean Science Data Analytics Platform for big ocean science at NASA's Physical Oceanography Distributed Active Archive Center (PO.DAAC) for big ocean science. It focuses on advancement and maturity by bringing together several NASA open-source, big data projects for parallel analytics, anomaly detection, *in situ* to satellite data matchup, quality-screened data subsetting, search relevancy, and data discovery. Our communities are relying on data available through distributed data centers to conduct their research. In typical investigations, scientists would (1) search for data, (2) evaluate the relevance of that data, (3) download it, and (4) then apply algorithms to identify trends, anomalies, or other attributes of the data. Such a workflow cannot scale if the research involves a massive amount of data or multi-variate measurements. With the upcoming NASA Surface Water and Ocean Topography (SWOT) mission expected to produce over 20PB of observational data during its 3-year nominal mission, the volume of data will challenge all existing Earth Science data archival, distribution and analysis paradigms. This paper discusses how OceanWorks enhances the analysis of physical ocean data where the computation is done on an elastic cloud platform next to the archive to deliver fast, web-accessible services for working with oceanographic measurements.

Keywords: big data, cloud computing, ocean science, data analysis, matchup, anomaly detection, open source

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INTRODUCTION

With increasing global temperature, warming of the ocean, and melting ice sheets and glaciers, impacts can be observed from changes in anomalous ocean temperature and circulation patterns, to increasing extreme weather events and more intense tropical cyclones, sea level rise and storm surges affecting coastlines can be observed, and may involve drastic changes and shifts in marine ecosystems. To date, investigative science requires researchers to work with many disjoint tools such as search, reprojection, visualization, subsetting, and statistical analysis. Researchers are finding themselves having to convert nomenclature between these tools, including something as mundane as dataset name and representation of geospatial coordinates. Sometime researchers are also required to transform the data into some common representation in order to correlate measurements collected from different instruments. The concept of an Integrated Data Analytics Platform (**Figure 1**) is to tackle these data wrangling, management, and analysis challenges, so researchers can focus on their investigation.

In recent years, NASA's Advanced Information Systems Technology (AIST) and Advancing Collaborating Connections for Earth System Science (ACCESS) programs have invested in developing new technologies targeting big ocean data on the cloud computing platforms. Their goal is to address some of the big ocean science challenges by leveraging modern computing infrastructure and horizontal-scale software methodologies. Rather than looking into developing a single ocean data analysis application, we have developed a data service platform to enable many analytic applications and lay the foundation for community-driven big ocean science.

OceanWorks (Huang, 2018) is a NASA AIST project to mature NASA's recent investments through integrated technologies and to provide the oceanographic community with a range of useful and advanced data manipulation and analytics capabilities. As an Integrated Data Analytics Platform, OceanWorks, harmonizes data, tools and computational resources to enable the ocean science community to focus on the investigation rather than spending time on security, data preparation, management, etc. One of the frustrations from the ocean science community has been experiencing with the growing silos of tools that lack coherence. A user might use one tool to search and has to manually translate the dataset name, time and spatial extends in order to satisfy the nomenclature of another tool (e.g., subsetting tool). OceanWorks is a 2-year development effort to implement an Integrated Data Analytic Platform for ocean science. This platform is designed to be extensible to promote community contribution with the following initial offerings:

1. Data analysis.
2. Data-Intensive anomaly detection.
3. Distributed *in situ* to satellite data matching.
4. Search relevancy.
5. Quality-screened data subsetting.
6. Upload and execute custom parallel analytic algorithm.

While the project is still in active development, in 2017 the OceanWorks project team donated all of the project's source code to the Apache Software Foundation and established the official Science Data Analytics Platform (SDAP) project[1] for community-driven and development of the data access and analysis platform for the cloud environment. The OceanWorks project is now developing in the open.

OCEANWORKS COMPONENTS

OceanWorks is an orchestration of several NASA big data technologies as a coherent webservice platform. Rather than focus on one science application, this webservice platform enables various types of applications. **Figure 2** show how to use OceanWorks to facilitate on-the-fly analysis of Hurricane Katrina (Liu et al., 2009) and to use a Jupyter notebook to interact with OceanWorks to analyze The Blob in the northeast Pacific (Cavole et al., 2016). This section discusses some of the key components of the OceanWorks.

Data Analytics

We have been developing analytics solutions around common file packaging standards such as netCDF and HDF. We evangelize for the Climate and Forecast (CF) metadata convention and the Attribute Convention for Dataset Discovery (ACDD) to promote interoperability and improve our searches. Yet, there is very little progress in tackling our current big data analytic challenges, which include how to work with petabyte-scale data and being able to quickly look up the most relevant data for a given research. While the current method of subsetting and analyzing one daily global observational file at time is the most straightforward, it is an unsustainable approach for analyzing petabytes of data. The common bottleneck is in working with large collections of files. Since these are global files, researchers are finding themselves having to move (or copy) more data than they need for their regional analysis. Web service solutions such as OPeNDAP and THREDDS provide a web service API to work with these data, but their implementation still involves iterating through large collection of files.

The OceanWorks' analytics engine is called NEXUS (Huang et al., 2016). It takes on a different approach for storing and analyzing large collections of geospatial, array-based data by breaking the netCDF/HDF file data into data tiles and storing them into a cloud-scale data management system. With each data tile having its own geospatial index, a regional subset operation only requires the retrieval of the relevant tiles into the analytic engine. Our recent benchmark shows NEXUS can compute an area-averaged time series hundreds time faster than traditional file-based approach (Jacob et al., 2017). The traditional file-based approach typically involves subsetting large collection of time-based granule files before applying analysis on the subsetted data. Much of the traditional file-based approach is spent on file manipulation.

OceanWorks enables advanced analytics that can easily scale to the available computation hardware along the full spectrum from an ordinary laptop or desktop computer, to a multi-node server class cluster computer, to a private or public cloud computer. The architectural drivers are:

1. Both REST and Python API interfaces to the analytics.
2. In-memory map-reduce style of computation.
3. Horizontal scaling so computational resources can be added or removed on demand.
4. Rapid access to data tiles that form natural spatiotemporal partition boundaries for parallelization.
5. Computation performed close to the data store to minimize network traffic.
6. Container-based deployment.

[1] http://sdap.apache.org

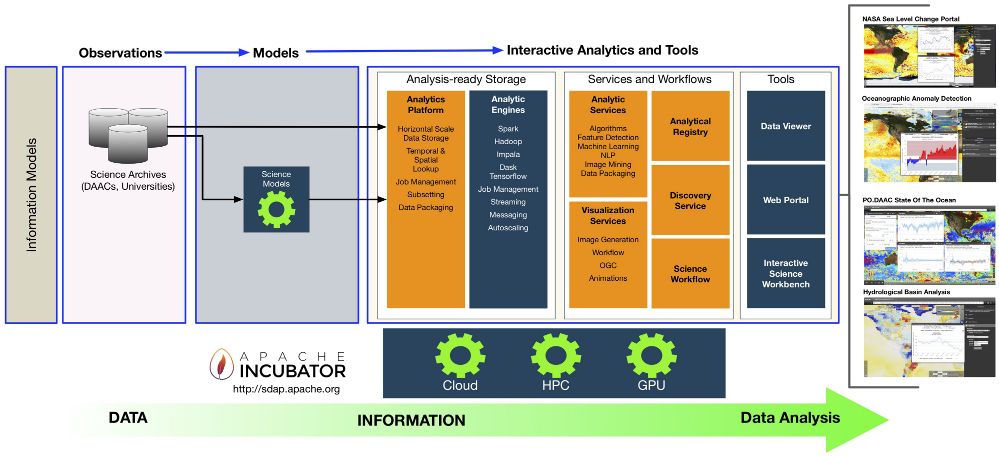

FIGURE 1 | An integrated data analytics platform.

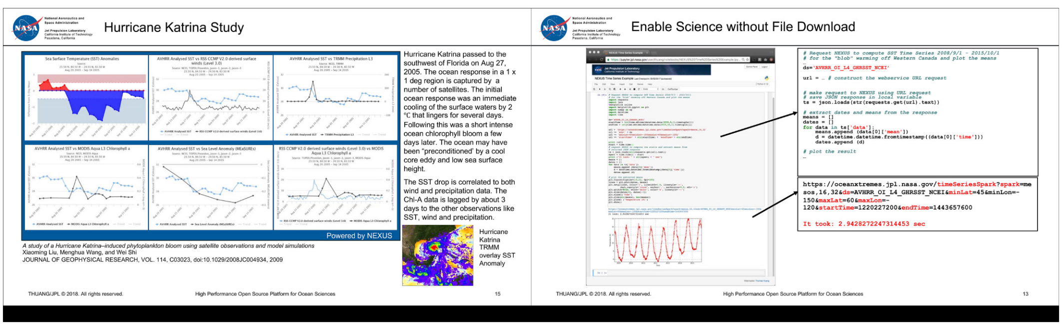

FIGURE 2 | Example oceanworks services.

The REST and Python API enables OceanWorks to be easily plugged into a variety of web-based user interface, each tuned to particular domains. Calls to OceanWorks from a Jupyter notebook enables interactive cloud-scale, science-grade analytics.

Built-in analytics are provided for the following algorithms:

1. Area-averaged time series to compute statistics (e.g., mean, minimum, maximum, standard deviation) of a single variable or two variables being compared. Optionally apply seasonal or low-pass filter to the result.
2. Time-averaged map to produce a geospatial map that averages gridded measurements over time at each grid coordinate within a user-defined spatiotemporal bounding box.
3. Correlation map to compute the correlation coefficient at each grid coordinate within a user-specified spatiotemporal bounding box for two identically gridded datasets.
4. Climatological map to compute a monthly climatology for a user-specified month and year range.
5. Daily difference average to subtract a dataset from its climatology, then, for each timestamp, average the pixel-by-pixel differences within a user-specified spatiotemporal bounding box.
6. *In situ* match to discover *in situ* measurements that correspond to a gridded satellite measurement.

In addition, authenticated or trusted users may inject their own custom algorithm code for execution within OceanWorks. An API is provided to pass the custom code as either a single or multi-line string or a Python file or module.

In situ to Satellite Matchup

Comparison of measurements from different ocean observing systems is a frequently used method to assess the quality and accuracy of the measurements. The matching or collocating and evaluation of *in situ* and satellite measurements is a particularly valuable method because the physical characteristics of the observing systems are so different and therefore the errors related to instrumentation and sampling are not convoluted. The satellite community tends to use collocated *in situ* measurements to develop, improve, calibrate, and validate the integrity of the retrieval algorithms (e.g., Bourassa et al., 2003). The *in situ* observational community uses collocated satellite data to assess the quality of extreme/suspicious values and to add spatial context to the often sparse point values. In both of these research realms there are many more detailed use cases, e.g., near real-time decision support of field programs, planning exercises for future observing system deployments, and development of integrated, *in situ* plus satellite data, global gridded analyses products that are useful for stand-alone research and for model initialization and boundary conditions.

There are several major data challenges related to successful satellite and *in situ* data collation research. Disparate data volume and variety is the primary challenge. Individual satellite collections are typically large in volume, have relatively homogenous sampling, are derived from a single platform, are composed of a consistent set of parameters, and are represented as scan lines, swaths, or globally gridded fields. *In situ* observations typically bring the variety challenge into the problem. They are often replete with heterogeneous observing platforms (ships, drifting and stationary buoys, glides, etc.), instrumentation types and sampling methods, highly varying sampling rates, and sparse spatiotemporal coverage over the global ocean. Another major challenge for collation-based research is logistical. The archives of satellite data and *in situ* data are often distributed at different centers, have a variety of access methods that need to be understood and applied, have different data formats and quality control information, and over time the data can dynamically extend (adding data to the time series) or have completely new versions with critical data quality improvements. The OceanWorks match-up service (Smith et al., 2018) resolves these major challenges and many other secondary challenges.

Quality-Screened Subsetting

When working with earth science data and information, whether derived from an *in situ* platform, or airborne or satellite instruments, users often need to access, understand and apply data quality information such as quality flags related to instrument and algorithm performance, physical plausibility, or other environmental characteristics or conditions. The ability to screen the physical data records via services that apply standardized sets of quality flags, states or conditions is imperative to allow scientists to seamlessly use these data to meet their requirements for error and accuracy.

In the oceanographic *in situ* realm there are a number of models and conventions in use by the community. The OceanWorks project has chosen the IODE (International Oceanographic Data and Information Exchange) convention (UNESCO, 2013), an internationally recognized and developed approach to tag *in situ* observations using both a primary and secondary level of quality flags. OceanWorks will screen *in situ* data using five primary level flags. This approach was chosen because of its simplicity which allows a direct mapping and transformation of the native quality flags embedded in the source *in situ* datasets (e.g., ICOADS, Freeman et al., 2017; SAMOS) into the IODE scheme.

In the oceanographic satellite realm, a similar need for standardization is exacerbated by the increasingly dense availability of quality information in the form of data accuracy, processing algorithms states and failures, environmental conditions, and auxiliary variables that are packed as conditions into quality variables represented as scalar or bit flags. This level of complexity makes it often difficult and confusing for a science user to understand and apply the proper flags to screen for meaningful physical data. The NASA software project, the Virtual Quality Screening Service (VQSS; Armstrong et al., 2016), addressed these issues by implementing a service infrastructure to expose, apply, and extract quality screening information through implementations of strategic databases and web services, data discovery, and exposure of granule-based quality information via interactive menus. Fundamentally, VQSS leveraged on the availability of Climate and Forecast (CF) metadata conventions applied to the satellite quality variables that strictly standardizes the structure and content of quality information through its attributes: *flag_values*, *flag_mask*, and *flag_meanings*. Employed web services are able to seamlessly extract physical information in the form of netCDF and JSON outputs based on screening conditions using these bit flag and scaler conditions, auxiliary variable for data threshold conditions, and many other use cases. OceanWorks will employ this architecture to allow users a similar capability to apply the quality information embedded in the gridded and ungridded input satellite data sources for sea surface temperature, ocean color, sea level, wind and precipitation parameters.

Search Relevancy and Discovery

Retrieving appropriate datasets is the prerequisite for data analysis, however, as the size of our archives increases faster than ever, it poses a great challenge for researchers and developers to efficiently identify the desired dataset(s). The PO.DAAC supplies the Earth science community with a large number of over 600 unique publicly accessible datasets collected by satellites and other missions. Although the PO.DAAC portal provides a valuable free text keyword search service to facilitate the searching process, it still has significant limitations including (1) the default keyword-based search method is popular in geospatial portals, which does not take semantic meaning of the query into account, for example, the search engine cannot retrieve metadata only containing "SLP" for a query "sea level pressure;" (2) Only single attributes are used in the default ranking algorithm in most geospatial portals, such as spatial resolution, processing level, monthly popularity instead of multidimensional preferences that should be considered in the ranking process; (3) The PO.DAAC portal's unsatisfactory implementation of data relevancy with useful datasets often buried in the search return list or non-existent. Improvements to data relevancy provides immediate improvements in the user search experience and result (Jiang et al., 2018a).

OceanWorks is equipped with a data discovery engine with a profile analyzer (Jiang et al., 2017), a knowledge base, and a smart engine. Raw web usage logs are collected from multiple servers and grouped into sessions through the profile analyzer. Reconstructed sessions are valuable sources of learning vocabulary linkages in addition to metadata (Jiang et al., 2017). A RankSVM model (Joachims, 2002) is trained on a few predefined ranking features with optimal ranking list provided by domain experts, aiming to increase the rank of data more relevant to the query (Jiang et al., 2018a). A recommender calculates the relevancy between metadata using their attributes and logs. A knowledge base is populated to store information like domain term linkages, metadata relevancy, as well as pretrained model for ranking and recommendation. When a user input a query in the search box, highly related terms are extracted from the knowledge base to expand the original search query and the search engine will retrieve data using the rewritten query instead of the input query, resulting in a higher recall score. The retrieved datasets are not be displayed to the user directly but reranked by the pretrained model to achieve a better ranking list. If the user chooses to view a metadata record, the recommender will retrieve a list of related datasets to the current dataset being viewed, helping the user efficiently find additional resources (Jiang et al., 2018b). In summary, the optimal workflow allows the data consumer to acquire dataset efficiently and accurately using advanced machine learning methods.

APPLICATIONS AND INFUSION

OceanWorks has been deployed for use by a number of NASA projects. Some of these include the NASA Sea Level Change Portal (SLCP), the GRACE Science Portal, and work is currently underway to integrate it with the State of the Ocean (SOTO) tool as part of the NASA PO.DAAC. Each project has slightly different needs, but all of them are able to utilize OceanWorks to fulfill their requirements.

The NASA SLCP contains a wealth of information about how the Earth's sea level is changing. It acts as a one-stop for everything from news articles to data analysis. OceanWorks has been deployed as the engine behind the Data Analysis Tool that is part of the portal. The Data Analysis Tool focuses on providing fast and easy to use data analysis on a curated list of datasets that are important to the understanding of sea level change. Because OceanWorks is able to be deployed in many configurations depending on project requirements, it was a perfect fit for providing the data analysis capabilities required by SLCP. In this particular instance, only a single instance of OceanWorks was required to power the analysis because the datasets being analyzed are limited in resolution and frequency. This allows for real-time interactive analysis through the JavaScript front-end.

Similar to the NASA SLCP, the GRACE Science portal has limited requirements with respect to the amount of data that needs to be analyzed. However, this project required deployment to a public cloud infrastructure with different network security constraints. So, while the user interface and data are similar in nature, the backend server is hosted using Amazon Web Services (AWS). This implementation is possible because OceanWorks provides the flexibility to be deployed on a laptop, a single server, a bare metal cluster, or on a public cloud.

The NASA PO.DAAC deployment has different requirements from both SLCP and GRACE. The datasets hosted by PO.DAAC are very large and cover a wide time period. In order to provide analysis capabilities for these larger datasets, more than one server is needed for analysis. OceanWorks was built for this situation and can utilize Apache Spark to scale horizontally and spread the compute requirements across a cluster of machines. With this cluster setup, OceanWorks is able to handle the analysis of larger, more dense datasets (**Supplementary Material**).

The multiple deployments of OceanWorks have proven that it is capable of handling a wide range of requirements and deployment scenarios. From single node to multi node, on premise to on cloud, and small data to big data, the flexibility and power of OceanWorks permits diverse implementation.

CHALLENGES AND OUTLOOK

The Apache Science Data Analytics Platform (SDAP) is the open source implementation of OceanWorks. The project team recognizes it will take years of collaborative effort to create a big data solution that satisfies the needs from various science disciplines. OceanWorks has demonstrated how to create a community-driven technology through a well-managed open source development process. Unlike many emerging Earth Science big data solutions, SDAP is designed as a platform with simple RESTful API that supports clients developed in any programming language. This façade-based architectural approach enables SDAP to continue to evolve and leverage any new open source big data technology. OceanWorks only addressed some of the ocean science needs. It requires contributions from our community to help continue to evolve this open source technology.

This project team would like this community to develop and infuse a common, open source, ocean analytic engine next to our distributed archives of ocean artifacts. Researchers or tool developers can interact with any of these analytics services, managed by the data centers, without having to move massive amount of data over the Internet.

AUTHOR CONTRIBUTIONS

All authors contributed to this community paper are members of the Apache open source NASA AIST OceanWorks project, called the Science Data Analytics Platform (SDAP).

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2019.00354/full#supplementary-material

REFERENCES

Armstrong, E. M., Xing, Z., Fry, C., Khalsa, S. J. S., Huang, T., Chen, G., et al. (2016). "A service for the application of data quality information to NASA earth science satellite records," in *Proceedings of the 2016 American Geophysical Union Fall Meeting*, San Francisco, CA.

Bourassa, M. A., Legler, D. M., O'Brien, J. J., and Smith, S. R. (2003). SeaWinds validation with research vessels. *J. Geophys. Res.* 108:3019. doi: 10.1029/2001JC001028

Cavole, L. M., Demko, A. M., Diner, R. E., Giddings, A., Koester, I., Pagniello, C. M. L. S., et al. (2016). Biological impacts of the 2013–2015 warm-water anomaly in the Northeast Pacific: winners, losers, and the future. *Oceanography* 29, 273–285. doi: 10.5670/oceanog.2016.32

Freeman, E., Woodruff, S. D., Worley, S. J., Lubker, S. J., Kent, E. C., Angel, W. E., et al. (2017). ICOADS release 3.0: a major update to the historical marine climate record. *Int. J. Climatol.* 37, 2211–2232. doi: 10.1002/joc.4775

Huang, T. (2018). "High performance open source platform for ocean sciences," in *Proceedings of the 2018 Ocean Sciences Meeting*, Portland, OR.

Huang, T., Armstrong, E. M., Chang, G., Chin, T., Gill, K., Greguska, F., et al. (2016). "NEXUS: platform for deep data analysis," in *Proceedings of the 2016 Federation of Earth Science Information Partners Winter Meeting*, Washington, DC.

Jacob, J., Greguska, F., Huang, T., Quach, N., and Wilson, B. (2017). "Design patterns to achieve 300x speedup for oceanographic analytics in the cloud," in *Proceedings of the 2017 American Geophysical Union Fall Meeting*, New Orleans, LA.

Jiang, Y., Li, Y., Yang, C., Hu, F., Armstrong, E. M., Huang, T., et al. (2018a). A smart web-based geospatial data discovery system with oceanographic data as an example. *ISPRS Int. J. Geo-Inf.* 7:62.

Jiang, Y., Li, Y., Yang, C., Hu, F., Armstrong, E. M., Huang, T., et al. (2018b). Towards intelligent geospatial data discovery: a machine learning framework for search ranking. *Int. J. Digital Earth* 11, 956–971.

Jiang, Y., Li, Y., Yang, C., Liu, K., Armstrong, E. M., Huang, T., et al. (2017). A comprehensive methodology for discovering semantic relationships among geospatial vocabularies using oceanographic data discovery as an example. *Int. J. Geogr. Inform. Sci.* 31, 2310–2328.

Joachims, T. (2002). "Optimizing search engines using clickthrough data," in *Proceedings of the ACM Conference of Knowledge Discovery and Data Mining*, Ithaca, NY: Cornell University.

Liu, X., Wang, M., and Shi, W. (2009). A study of a hurricane katrina-induced phytoplankton bloom using satellite observations and model simulations. *J. Geophys. Res.* 114:C03023.

Smith, S. R., Elya, J. L., Bourassa, M. A., Huang, T., Tsontos, V. M., Holt, B., et al. (2018). "Integrating the distributed oceanographic match-up service into ocean works," in *Proceedings of the 2018 Ocean Sciences Meeting*, Portland, OR.

UNESCO (2013). *Paris. Intergovernmental Oceanographic Commission of Ocean Data Standards, Vol.3: Recommendation for a Quality Flag Scheme for the Exchange of Oceanographic and Marine Meteorological Data*. Paris: UNESCO.

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Building the Knowledge-to-Action Pipeline in North America: Connecting Ocean Acidification Research and Actionable Decision Support

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Ocean acidification (OA) describes the progressive decrease in the pH of seawater and other cascading chemical changes resulting from oceanic uptake of atmospheric carbon. These changes can have important implications for marine ecosystems, creating risk for commercial industries, subsistence communities, cultural practices, and recreation. Characterizing the extent of acidification and predicting the ramifications for marine and freshwater resources and ecosystem services are critical to national and international climate mitigation discussions and to local communities that rely on these resources. Based on critical grassroots connections between scientists, stakeholders and decision makers, "Knowledge-to-Action" networks for ocean acidification issues have formed at local, regional and international scales to take action. Here, we review three examples of North American groups elevating the issue of ocean acidification at these three levels. They each focus on developing practicable, implementable steps to mitigate causes, to adapt to unavoidable change, and to build resilience to changing ocean conditions in the marine environment and coastal communities. While these first steps represent critical efforts in protecting ecosystems and economies from the risks posed by ocean acidification, some challenges remain. Sensitivity and risk to OA varies by region, species and ecosystems; priorities for action can vary between multiple and conflicting partners; evidence-based strategies for OA risk mitigation are still in the early stages; and gaps remain between scientific research and actionable decision-maker support products. However, the scaled networks profiled here have proven to be adept at identifying and addressing these barriers to action. In the future, it will be critical to expand funding for food web impact studies and development of decision support tools, and to maintain the connections between scientists and marine resource users to build resilience to ocean acidification impacts.

Keywords: ocean acidification, ocean observations, observation networks, knowledge-to-action, risk mitigation, decision support, climate resilience

INTRODUCTION: ALARM BELLS, EARLY ACTORS, AND THE VALUE OF COLLABORATION

Concern about ocean acidification as a scientific issue and a marine resource management concern has grown rapidly over the last decade, as the present and future impacts of this global ocean change have come into focus. Ocean acidification (OA) refers to the suite of chemical changes caused by the oceanic absorption of anthropogenic carbon dioxide (CO_2) from the atmosphere (reviewed at length in Gattuso and Hansson, 2011, and summarized in other papers in this volume). Briefly, the ocean absorbs about one-quarter of CO_2 released annually by anthropogenic activities (Le Quéré et al., 2014). When CO_2 dissolves in seawater it produces a weak acid, which lowers seawater's pH and increases its acidity. Average ocean pH has dropped by about 0.1 units since the start of the Industrial Revolution, corresponding to about a 30% increase in acidity (IPCC, 2013). Seawater pH is projected to drop 0.4 to 0.5 units by 2100 (Orr et al., 2005; IPCC, 2013).

The resulting chemical changes could have significant consequences for many marine ecosystems and marine ecosystem services. Calcifying organisms that build shells, skeletal structures, and hard parts from calcium carbonate frequently cannot build or maintain these carbonate structures under acidification, resulting in declines in growth and survival (e.g., Fabry et al., 2008). Even non-calcifying organisms are at risk: sensory, behavioral, and food-web impacts of OA have also been identified by the research community (Guinotte and Fabry, 2008; Munday et al., 2009; Simpson et al., 2011; Ou et al., 2015; Marshall et al., 2017). Metabolic responses to OA alter some organisms' energetic budgets (e.g., Francis Pan et al., 2015), and may even change the quality of seafood: both altered taste (Dupont et al., 2014) and lower protein, lipid, and carbohydrate contents (Lemasson et al., 2019) have been noted.

Worldwide, experts are concerned that progressing OA will cause cumulative ecosystem level shifts that put human communities at risk– possibly by reducing the overall economic value of commercial fisheries (Cooley and Doney, 2009; Narita et al., 2012; Clements and Chopin, 2016); eroding food security, especially for communities that rely on subsistence harvests as their primary source of protein (Garcia and Rosenberg, 2010; Lam et al., 2014; Mathis et al., 2015), or driving cultural losses in native and tribal settings (Lynn et al., 2013; Metcalf, 2015; Wassillie and Poe, 2015). Ecosystem services such as capture fisheries, aquaculture, and traditional and recreational harvesting from key marine taxa and environments are expected to be highly impacted from high CO2 emissions (Gattuso et al., 2015) and other global change stressors, with implications of food security for vulnerable peoples.

These concerns have emerged in part because of early manifestation of real-world acidification impacts. In the early 2000 s, massive die-offs of oyster larvae in Pacific Northwest (PNW) hatcheries were attributed directly to acidification from anthropogenic carbon dioxide (Barton et al., 2015). This phenomenon threatened the Pacific oyster aquaculture industry, which supports over 3200 jobs and brings in \$270 million annually (Washington State Blue Ribbon Panel on Ocean Acidification, 2012).

Subsequent research has suggested that similar impacts could emerge in other areas that host vulnerable species, both reducing current populations and slowing growth in expanding industries. For example, commercial fishing in Bristol Bay, Alaska employs 12,400 people and generates 162 million dollars in labor income in each year. Most of these jobs come from harvests of sockeye salmon and other high-value species such as crab (McDowell Group, 2017), populations that are also susceptible to ocean acidification. Acidification directly affects calcification and growth of Alaskan crab species in laboratory studies (Long et al., 2013a,b), and behavior and predator-prey relationships of salmon (e.g., Ou et al., 2015), which could lead to population declines. Other concurrent stressors such as sea level rise will also affect coastal productivity and create conflict between terrestrial and aquatic food production systems; increased crop production or changes in precipitation patterns can lead to increased agricultural run-off into coastal systems, and further decreasing pH due to eutrophication (Cottrell et al., 2018).

Coral reefs are expected to be heavily altered. Combined with rising sea temperatures, some models project that 92% of coral cover will be lost by 2100 (Speers et al., 2016). This could lead to declines in fish landings for populations that rely on reefs for habitat (Hughes et al., 2017). Given the prevalence of coral reefs in the tropical Pacific, these impacts could be especially severe for Australia and the Pacific Islands (Johnson et al., 2015; Hoegh-Guldberg et al., 2017).

Population declines of this nature can be expensive. The projected value of coral reef tourism in Australia is approximately AU $5-6 billion per year. Four of the ten most valuable marine fishery species in the United Kingdom are based on calcifying shellfish vulnerable to acidification (Le Quesne and Pinnegar, 2011). Losses in these fisheries alone could result in losses as high as £379 million pounds per year by the end of the decade, with additional losses as high as £125 million annually possible for the aquaculture industry (Cheung et al., 2012; Pinnegar et al., 2012). The Atlantic sea scallop industry represents more than $500 million in annual landings for the United States East coast (National Marine Fisheries Service, 2012). Models predict that ocean acidification could reduce populations by as much as 50% in the coming decades (Cooley et al., 2015; Gledhill et al., 2015). Ocean acidification could also negatively impact scallop aquaculture in Australia (Richards et al., 2015) and Chile (Yañez et al., 2017).

Even in growing fisheries, ocean acidification is expected to have an impact. Potential increases in revenue from Arctic marine capture fisheries could reach nearly 40% in the coming decades (Lam et al., 2014). However, ocean acidification is expected to reduce the catch potential in those fisheries, slowing growth and other economic indicators. The consequences of OA are especially prevalent for Finland, Canada, and Greenland, where revenues are projected to decrease by more than 20%. Across the entire Arctic region, slowed growth could represent losses of $390 million per year in total economic output (Lam et al., 2014).

The description of these risks and vulnerabilities are based in part on the systematic response to acidification exposure developed as a rapid reaction to the economic fallout of the acidification-mediated PNW larval collapse in 2015. The immediate impact to the industry quickly drove research developments and policy action in Washington State and the PNW region that identified nascent risks to the industry, quickly changed practices to reduce exposure to those risks as much as possible, and supported preparation for future ocean changes. This collaborative, multidisciplinary, comprehensive regional response has informed the development of proactive steps implemented in other regions across the United States which aim to prevent the types of socioeconomic impacts as were seen in Washington. Most importantly, best practices are beginning to evolve around how OA knowledge and theory can be turned into action that prepares communities for the future.

Rooted in that initial response effort and the growing knowledge of OA risks around marine economic drivers worldwide, this paper describes the developing ocean acidification "knowledge-to-action pipeline" in North America (abbreviated here as the Pipeline). The Pipeline illustrates emerging sets of best practices to successfully mitigate and adapt to ocean acidification risks (**Figure 1**) that (a) improve the efficiency and speed by which actions yield results; (b) expand the breadth of community engagement and support for this work; (c) target specific needs; and (d) produce lasting benefits. In general, these recommendations can be applied across diverse communities and varying situations and scales.

Relationship building is critical to each of these steps (**Figure 2**). In the next section of this paper, we present three case studies at local, regional, and international scales that provide particular evidence about the importance of successful partnership building. In the third section, we present case studies describing the development of actionable, concrete strategies to address OA, based on these relationships.

In the fourth section of this paper, we synthesize the commonalities across these efforts to suggest that the Pipeline has two main elements: (1) partnership building and (2) action planning, each with clear implications for the development of existing and new ocean observation networks. We conclude the paper with a look at obstacles in the Pipeline, and how best to meet these challenges as applications expand in the future.

FROM KNOWLEDGE TO ACTION: RELATIONSHIP BUILDING

The Earliest Days

Impacts from ocean acidification first manifested in the Pacific Northwest United States, affecting the hatcheries that supply the entire Pacific oyster aquaculture industry on the United States West Coast (Barton et al., 2011). Extremely high larval mortality resulted in major seed production declines. Given that most oyster seed stock reared around the nation comes from larval hatcheries in the Pacific Northwest, the issue had far-reaching impacts.

Immediately, marine users and resource managers began to search for solutions. Responding to this urgent need, a collaborative multi-disciplinary group of federal and academic scientists and private shellfish growers came together to identify the cause of the larval oyster mortality. This group grew out of several long-standing personal and professional relationships among federal and academic scientists and shellfish growers (Barton et al., 2015). Very soon, this small group grew into an interdisciplinary network of scientists, resource managers, industry and others from local, state, federal and tribal entities that came together to advance the understanding of ocean acidification and its effects on biological resources of the United States West Coast (Feely et al., 2012; Barton et al., 2015). Infrastructure support from existing national programs like Sea Grant and the U.S. Integrated Ocean Observing System helped ultimately to solidify these partnerships into the California Current Acidification Network (C-CAN).

At the same time, industry experts petitioned Washington State leaders at multiple levels of government for OA solutions. Two top-down outcomes followed: The industry group received NOAA funding for enhanced monitoring of OA (Barton et al., 2015), and the Washington State Governor convened the state's Blue Ribbon Panel on Ocean Acidification in 2012 to determine how to address the causes and consequences of ocean acidification. Importantly, panel members included state lawmakers, state resource managers and water quality experts, tribes, and impacted industry, and OA scientists, and they were

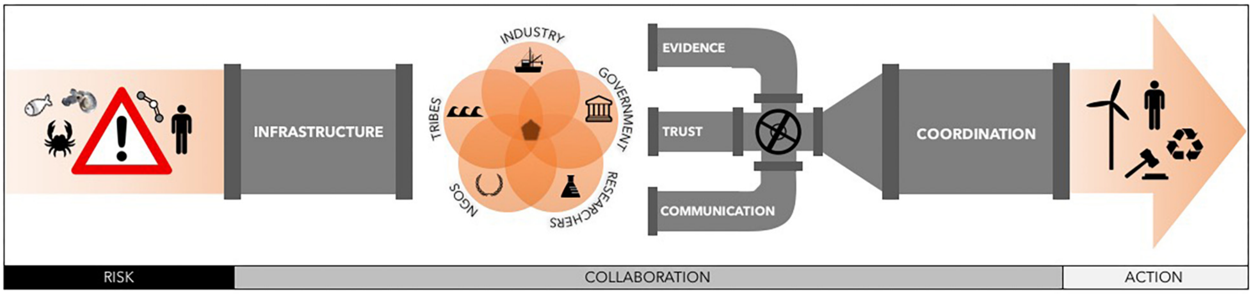

FIGURE 1 | Stages in the Knowledge-to-Action Pipeline. Information about risk is transferred through existing and amplified infrastructure to diverse stakeholders that all closely collaborate together. By building a body of evidence, mutual trust, and consistent communication practices, these bodies can coordinate to produce actions.

charged to identify concrete actions for the state to implement in response to the observed impacts of ocean acidification.

The scientific results and network emerging from C-CAN contributed greatly to the Panel's work. The Blue Ribbon Panel's report (Washington State Blue Ribbon Panel on Ocean Acidification, 2012) identified 42 consensus actions to directly assist in the rebuilding and protection of the local oyster industries, many of which have already been implemented. Since 2012, the Washington legislature has created and sustained a Marine Resource Advisory Council to maintain progress on specified actions. The group has demonstrated follow-through: a 5-year review was recently completed in 2017 (Washington State Blue Ribbon Panel on Ocean Acidification, 2017).

The Importance of Investing Locally: United States Coastal Acidification Networks

Building on the success of C-CAN, NOAA's Ocean Acidification Program and the U.S. Integrated Ocean Observing Systems (IOOS) Regional Associations have committed to growing this model around the country. Regional Coastal Acidification Networks (CANs) build public knowledge of the regional drivers and impacts of coastal and ocean acidification, coordinate stakeholder needs, and facilitate action through connections to scientists and policymakers.

Since the establishment of the California Current Acidification Network (C-CAN) in 2009, six operational CANs have formed around the country, including members from academia, industry, and both governmental and non-governmental organizations. The CANs provide a communication infrastructure to coordinate these diverse partners and equip United States regions with the tools needed to adapt to ocean and coastal acidification. CANs share specific elements, described below, which contribute to their sustained success.

Elements of Successful CANs

Diverse partnerships

CANs convene a variety of entities such as state agencies, researchers, industry, tribal members, and concerned citizens on an equal footing (**Figure 2**). A shared vision unites them; together they work to assess how changes in ocean and coastal chemistry are manifesting in the region, identify gaps, and develop mitigation strategies. Because of their strong connections to communities, user groups, and local expertise, CANs are best positioned to help air community concerns and develop trust at the grassroots level among multiple sectors.

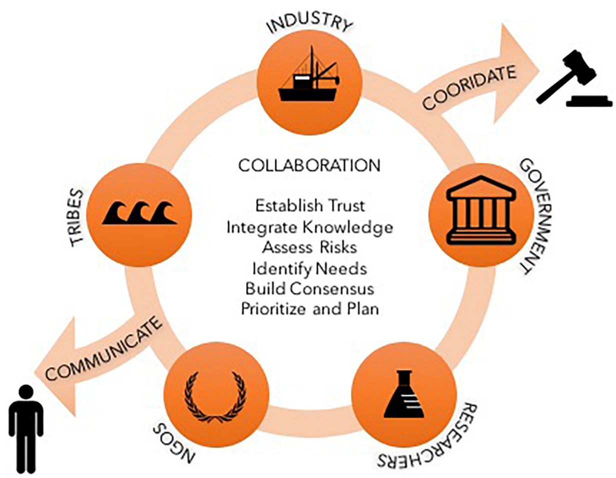

FIGURE 2 | Elements of successful coordination relationships exemplified by the Coastal Acidification Networks, and utilized by other networks profiled in these case studies. Successful CANs bring together diverse voices to establish trust, integrate knowledge, assess risks, identify needs, build consensus, and prioritize and plan responses to OA risks. Through these efforts, they can successfully communicate with the public and coordinate their efforts to efficiently advocate for specific actions.

Communication

A key ingredient of a successful CAN is communication (**Figure 2**). The structure provided by the group helps facilitate ongoing conversations around the latest scientific results and observations, stakeholder concerns, and seeks to achieve participant consensus. Specifically, many CANs focus on communicating the state of the science, regional approaches to monitoring, and identifying vulnerable species and ecosystem hotspots. Disseminating this information and building relationships among different community sectors are based in good communication practices: many CANs use websites as an information hub for stakeholders, use an email list serve to foster communication among network members, and host webinar series to share stakeholder perspectives, research highlights, and management needs related to coastal and ocean acidification.

Targeted working groups

While communication strategies help educate stakeholders and decision makers about new and ongoing scientific research related to ocean acidification, one of the best tools developed by the CANs are regional working groups focused around particular stakeholders or risks. For example, The Northeast Coastal Acidification Network (NECAN) Industry Working Group was established to facilitate communication among industry members (including aquaculturists and fishermen) and leading ocean and coastal acidification experts to understand and respond to industry concerns about acidification risks. One outcome of this group already is the agreement by industry representatives that they need advance warning of any changes which might impact their business. NECAN has made developing this decision support output a central goal for the near future.

Continuing this theme, NECAN will be hosting a workshop at the Northeast Aquaculture Conference and Exposition (NACE) in the winter of 2019 where industry members can learn more about how acidification may impact their livelihoods in concert with other changes, and where scientists and federal agency representatives can hear from industry members about what advance information would be most useful to them. The conversation will be designed to help identify existing gaps in knowledge and monitoring that would impede development of the desired OA forecasts, and to help guide future research investment. The results from the Industry Working Group and the recommendations from NACE will be shared with the Maine State Commission and the New Hampshire State Commission through the NECAN Management and Policy Working Group to help shape future state-supported actions.

Key Outcomes From CAN Collaborations

The CAN experience has resulted in local research and monitoring plans that emphasize both research gaps and stakeholder needs, ensuring that developing research leads to actionable decision support products. Currently, the Mid-Atlantic Coastal Acidification Network (MACAN) is developing its regional plan to expand monitoring. Considerable uncertainty still exists for Mid-Atlantic species around acidification effects on individual fitness, biodiversity, and predator-prey interactions. Highly variable observed responses, small-scale laboratory experimental scenarios, and limited species-specific and ecosystem-scale acidification studies limit researchers' ability to assess present and future impacts on ecosystems and coastal communities. Additional environmental stressors and the acclimation or adaptation potential of individuals and populations could likely play opposing roles under acidification scenarios. Whether this results in net exacerbation or alleviation of ecosystem stress is as yet unknown. However, to what extent the relative contribution of these drivers will impact the overall Mid-Atlantic ecosystem needs to be investigated. To this end, MACAN has identified existing monitoring efforts, clear research gaps, relevant research priorities, and recommendations for optimizing additional monitoring, due for release in 2019.

Recommendations for Local Collaboration Networks

Truly effective collaboration is key to the success of the regional CANs. At every step, the CAN recipe depends on the ingredients discussed above to be successful: diverse partners, communication, and targeted working groups (**Figures 1**, **2**). As a result of this collaboration, CANs have become very successful local-to-regional grassroots organizations. Others in the ocean observing community seeking a knowledge-to-action approach at this level should consider the following recommendations:

- Bring together a collaborative and diverse team around a given issue (no more than 15 people). The leadership team should include multidisciplinary science perspectives and multiple private sector entities to ensure that all stakeholders have a voice in the CAN.
- Compile and assess regional needs through stakeholder engagement at all levels (government, academia, non-profit, industry, etc.).
- Assess existing efforts and identify gaps and areas of opportunity.
- Fill information gaps through strategic funding efforts.
- Continue engagement with stakeholder groups, keeping them up to date, as well as encouraging additional input.

Regional Collaborations That Cross National Borders: A Framework for Action on Western Arctic Acidification

Many of the lessons learned from the early CAN efforts are already being applied at a much larger scale. Here, we profile a relatively young observational network for acidification that is incorporating these recommendations as it starts to scale up: the joint Canadian-United States Collaborative Framework for Western Arctic Acidification.

Structures that coordinate research in vulnerable, rapidly changing regions where knowledge is lacking can be invaluable to advancing research and action. In the Arctic, acidification research is at a much earlier stage than in other areas, given that harsh conditions and remote territory limits data gathering, and sea ice presents a serious hazard to long-term monitoring equipment. Nevertheless, acidification in the Arctic is progressing rapidly (Mathis et al., 2015; AMAP, 2018; Cross et al., 2018) and the region is commonly referred to as a bellwether for ocean acidification impacts (Fabry et al., 2009).

In June 2016, Canadian Prime Minister Justin Trudeau, American President Barack Obama and Mexican President Enrique Peña Nieto met in Ottawa for the North American Leaders Summit. Participants recognized the need to provide global leadership and enhanced cooperation on the impacts of climate change on oceans and marine ecosystems. In support of the international commitments made at this Summit, members of Fisheries and Oceans Canada (DFO) and the United States National Oceanic and Atmospheric Administration (NOAA) held an initial meeting in Canada in September 2016 to discuss impacts of OA on marine resources, share research methodologies for OA monitoring and mitigation, and identify opportunities for collaborative efforts.

Following this auspicious start, the DFO-NOAA Ocean Acidification Coordination Committee was formed in 2017, operating under an existing Environment Canada and Climate Change – NOAA Memorandum of Understanding. A finalized Collaboration Framework on Ocean Acidification formed two Working Groups: (1) the Monitoring Working Group, and (2) Research, Experimentation and Modeling Working Group, both of which are co-led by DFO and NOAA scientists. Membership of each group consists of DFO, NOAA or NOAA-funded scientists with expertise including: biogeochemical, physical, biological and ecosystem modeling; observation and data synthesis; and, experimental and field biological effects research.

So far, the key successful actions of the DFO-NOAA Collaboration Framework have come from the working groups. Much like the CAN model for establishing regional observation networks, both groups are beginning their efforts by developing inventories of monitoring, biological research and modeling efforts that are underway. To facilitate collaboration, both groups are also developing best practices for monitoring or research and experimentation tailored to bilateral concerns, developing OA communication activities and results between DFO and NOAA, and promoting knowledge sharing via joint meetings and collaborative opportunities.

The Monitoring Working Group specifically aims to establish priority areas including shared areas of concern, such as regional hotspots; coordinate cruises; and identify expertise and infrastructure gaps hindering geochemical understanding of OA. The Research, Experimentation and Modeling Working Group specifically aims to identify shared fauna of concern and appropriate actions to take; and identify gaps in expertise, biological research or infrastructure that hinder biological understanding of OA impacts and reduce modeling accuracies.

As the group focuses on the goals of two federal agencies, existing infrastructure to communicate and address stakeholder needs are relied upon. Fortunately, close connections already exist between the leadership and working group participants and regional stakeholder coordinating groups, such as the CANs. In particular, the Alaskan and Northeastern CANs have been a critical resource for educating researchers and the federal leadership. Helpfully, the CANs have a close and deliberate connection to NOAA. Additionally, many of the working group participants also participate in other Arctic coordination efforts, including the Synthesis of Arctic Research (SOAR) Program, the Inter-agency Arctic Research and Policy Committee (IARPC), working groups of the Arctic Council, such as the Distributed Biological Observatory Program (DBO), and the Arctic Marine Assessment Programme (AMAP).

These outside groups have all identified key hotspots and ecosystems that may be affected by ocean acidification, and which council the DFO-NOAA working groups on their recommendations. For example, the recent Arctic Marine Assessment Program (AMAP) report on ocean acidification profiled five ecosystems that may be at risk from ocean acidification (AMAP, 2018). The monitoring working group is advocating for an expansion of the Distributed Biological Observatory hotspot program that will address North American Arctic acidification concerns outlined in the AMAP report.

Recommendations for Regional Collaboration Networks

The key benefits of this federal bilateral initiative are to advance and integrate multidisciplinary ocean acidification science efforts, promote collaboration to enhance program delivery, and to facilitate effective resource management in a changing ocean. Coordination that crosses international boundaries in particular can break down data silos and increase information sharing and access.

- Leverage existing diplomatic infrastructure that enables easy collaboration across borders.
- Build specific coordination infrastructure for the key research topic.
- Assess existing efforts to identify gaps and opportunities for growth, encouraging synthesis and data sharing agreements between entities.
- Create bridges to diverse stakeholder organizations within each entity that help generalize priorities across local regions and identify important regional priorities.

From Regional to Global: International Alliances

The Pacific Coast Collaborative (PCC), representing the United States states of California, Oregon, Washington, and the Canadian province of British Columbia, was formed in 2008 when the leaders of the participating states and province agreed to work together as a region on energy, climate, and ocean health issues. Following the PNW larval oyster losses in the 2000 s that gave rise to WA state action supported and informed by C-CAN, the PCC has been working to address the causes and impacts of ocean acidification together as a region since 2010, including calling for more investment in scientific research and monitoring.

In 2013, the PCC member jurisdictions convened the West Coast Ocean Acidification and Hypoxia Science Panel (Chan et al., 2016), responding directly to recommendations put forward by the Washington State Blue Ribbon Panel. Comprised of scientists from across the region, the WCOAH Panel focused on ocean acidification and hypoxia impacts on the ecosystems and economies across the west coast of North America and recommended a series of local and regional strategies for addressing the challenge. In addition to recognizing the central importance of mitigating carbon emissions in developing solutions, the WCOAH Panel stressed the value of improving the West Coast monitoring enterprise of both physical and biological factors. The WCOAH Panel recognized that a rigorous understanding of OAH trends and biological responses would allow for more effective and strategic investments in adaptation and mitigation measures.

To make progress on this WCOAH Panel recommendation, the PCC convened the Joint Ocean Acidification and Hypoxia Monitoring Task Force (Task Force) in 2016, in partnership with the federal Interagency Working Group on Ocean Acidification (IWG-OA). The goal of the Task Force was to inventory the OAH monitoring infrastructure along the North American Pacific Coast and provide easy public access to the results.

Completed in 2018, the monitoring inventory now contains records from over 125 participants describing over 200 projects from Alaska to Baja California. The monitoring efforts described in the inventory are capturing trends in OAH occurring across the region and helping scientists and decision-makers better understand and respond to potential impacts to key species and ecosystems.

The monitoring inventory also sets the stage for a collaborative region-wide gap analysis. This analysis will inform the design of a West Coast Integrated OAH Monitoring network that efficiently leverages existing assets and supports subsequent strategic monitoring investments. The ultimate goal is to have a functioning coast-wide monitoring network that effectively answers management questions about ocean acidification and hypoxia and informs actions that reduce impacts, improve resiliency and support adaptive management.

Responding to a subnational call for climate and ocean leadership unleashed by the COP21 Paris Climate Agreement negotiations in 2015, and to advance the impacts of existing state and regional collaboration on an international scale, the West Coast jurisdictions formed and launched the International Alliance to Combat Ocean Acidification (OA Alliance) in December 2016. The OA Alliance brings together governments and partners concerned about the impact of carbon on our oceans and are ready to take meaningful actions to address these changes (International Alliance to Combat Ocean Acidification, 2016).

The intent of the OA Alliance is to motivate governments to proactively respond to the impacts of ocean acidification by charting a course of action for sustaining coastal communities and livelihoods. OA Alliance members work together to raise awareness about ocean acidification. They commit to take individual actions that address the environmental and economic threat posed by ocean acidification within their region by creating their own unique OA Action Plan. Members are also calling for emissions reductions and ocean adaptation and resiliency actions under applicable climate frameworks like the United Nations Framework Convention on Climate Change (UNFCCC) and the United Nations Sustainable Development Goals (UN SDGs.) Ultimately, the best mitigation plan for ocean acidification is to drastically curb carbon emissions, which will require ongoing commitments to international collaboration.

Since its launch in December of 2016, the OA Alliance has grown to over seventy members including eleven national governments, eight states, two provinces, six tribal nations, and four cities, along with research institutions, businesses and NGOs.

The OA Alliance is not alone in its efforts and has strategically identified and built relationships with strong partners and potential new members each month, ultimately securing commitments to collaborate across organizations and increasing commitments to join. The OA Alliance has been steadily increasing the number of government and affiliate members that are regularly engaged with OA Alliance efforts which provides diversity of membership from members focused on impacts from the Arctic to the Indian Ocean.

Other organizations also support international ocean acidification research and action. The Ocean Acidification International Coordination Centre (OA-ICC) specifically promotes the development of data management tools and standardized methodologies and best practices for ocean acidification research. Housed under the International Atomic Energy Agency, the OA-ICC focuses on peaceful applications of nuclear and isotopic techniques (e.g., geochronology; paleo-climatology; isotopic uptake rates) for ocean acidification research. This group has also formed extensive collaborations and extra-budgetary coordinated research projects that support research into the biological and social effects of ocean acidification. We also encourage interested readers to consider the comprehensive review of the Global Ocean Acidification Observing Network (see Jewett et al., 2019 this volume). Briefly, this organization focuses on OA science in order to document the status and progress of ocean acidification on the global scale and in coastal environments, to understand the chemical drivers and ecosystem-level impacts of ocean acidification, and to coordinate members to provide spatially and temporally resolved biogeochemical data necessary to optimize modeling for ocean acidification.

Creating Decision-Maker Support Tools

While organizations like GOA-ON and the OA-ICC help to coordinate research that is critical for the ultimate creation of decision support tools, the OA Alliance is unique in that it specifically focuses on governmental action on the international scale. Critical to its mission, the OA Alliance has engaged with members in the development of jurisdictional OA Action Plans that will describe real, tangible actions that governments will take to respond to the threat of ocean acidification. The OA Alliance has made international commitments with the UN SDG 14.3 and at the 2017 Our Ocean Conference to support the development of twenty OA Action Plans by the end of 2019. The Alliance is well on pace to meet that goal with Washington, California, Oregon, and New Zealand Action Plans all completed or nearly completed, and several more to follow including those from City of Vancouver in British Columbia, Netherlands and Fiji.

To aid governments in this process, the OA Alliance created an OA Action Plan Toolkit (International Alliance to Combat Ocean Acidification, 2017), a strategic process for starting to develop a plan. The toolkit draws from a compendium of best practices and recommendations stemming from published state, regional, and national ocean action plans, as well as ocean acidification action plans or ocean acidification commission recommendations in the United States. It makes recommendations for actions across five categories: (1) advancing scientific understanding; (2) mitigation; (3) adaptation and resiliency actions; (4) public awareness and outreach; and (5) elevating climate related impacts to oceans within international climate frameworks. The OA Alliance encourages member governments to consider "right sized" and locally specific actions within each category.

The OA Alliance has also hosted member-driven webinars on topics including using the OA Action Plan Toolkit, member updates on their action planning processes, a tutorial of the newly launched OA Information Exchange hosted by NOAA Ocean Acidification Program, techniques and pilot projects focused on carbon sequestration through the use of submerged aquatic vegetation, existing monitoring networks and tools for beginning new monitoring sites and expanding regional networks, incorporating ocean acidification adaptation and resiliency actions into Nationally Determined Contributions called for by the Paris Climate Agreement, and how actions by cities can address ocean acidification locally.

What has become increasingly clear through the rapid growth of the OA Alliance in just 2 years is the interest from high-level policy and decision-makers to become more engaged with scientists who will help them better understand local impacts to key marine resources within their regions. Government members of the OA Alliance are learning from each other about the policy frameworks they will use to address a suite of mitigation, adaptation and resiliency strategies that are needed to robustly respond the potential impacts of ocean acidification, while also managing for force-multiplying factors of temperature and dissolved oxygen changes over time.

While the OA Action Plan provides a platform for governments to think about various policy implementation pathways, including increased funding for more advanced monitoring, it's not intended to be a prescriptive set of policies or exactly replicable framework that will work for all governments. Increasingly the priority for member governments joining the OA Alliance is to learn about processes for convening the right set of actors that will produce a series of local or regional recommendations and then, importantly, how existing management frameworks can incorporate and sustain new investments and actions over time.

Just as some ocean acidification science is in beginning stages, policy response and management discussions are also in beginning stages, making early and frequent collaborations across government, scientists, and impacted industry at a regional level all the more beneficial.

Recommendations for International Collaboration Networks

The strength of the OA Alliance comes from members working together (i.e., **Figure 2**), committing to taking concrete action and sharing best practices for effective mitigation and adaptation management frameworks for ocean acidification at a local, regional and international level. The OA Alliance serves a unique role by inspiring political commitments and policy actions through the high-level leadership of its government members. The following recommendations are taken directly from the OA Alliance mission statement:

- Create a coalition of governments and partners at all stages of OA learning to elevate the visibility and importance of ocean acidification in public discourse and policy development.
- Support governments to take meaningful actions to address changing ocean conditions by creating actionable decision support products.
- Push for inclusion of strong ocean protection provisions in international climate agreements and other relevant frameworks to build sustained support for addressing this global problem.
- Advance scientific understanding and expand public awareness and understanding of acidification.

The Global Ocean Acidification Observing Network (GOA-ON), formed in 2012, provides input to the last of these recommendations (see Tilbrook et al., 2019 this volume; Newton et al., 2015). Organized at the global scale, GOA-ON has assembled a network of over 500 scientists from more than 80 countries, and reaches out to members all over the world who are working to understanding OA on local to global scales. Through this collaborative international approach, GOA-ON seeks to document the status and progress of OA in open-ocean, coastal, and estuarine environments, to understand the drivers and impacts of OA on marine ecosystems, and to provide spatially and temporally resolved biogeochemical data necessary to optimize modeling for OA parameters. Accordingly, GOA-ON works to provide the critical Knowledge piece of the Knowledge-to-Action Pipeline.

Lessons learned from existing international collaboration efforts include:

- The power of government and non-government collaboration and partnerships within one region;
- The importance of engaging political leadership at a high-level;
- Focus on long-term implementation mitigation, adaptation and resiliency strategies over time;
- Government to government info- exchange is invaluable and appreciated, even if regions are not experiencing exactly similar issues or managing for the same resources.

FROM MONITORING NETWORKS TO OA ACTION PLANS

A case study from California illustrates how the OA Alliance is providing a platform for governments to engage in the Knowledge-to-Action pipeline.

The California Ocean Protection Council, in cooperation with the California Ocean Science Trust, has undertaken the development of a State of California Ocean Acidification Action Plan (Phillips et al., 2018). The policy and management action plan is the first of its kind for the state of California and was developed within the framework of the OA Alliance.

California's plan relies heavily on scientific data as a basis for action, such as data inputs and information on monitoring instrumentation, research on species sensitivity, oceanographic and ecosystem modeling, social science, education, and communication provided through federal partnerships with NOAA's regional observation networks established through the U.S. Integrated Ocean Observing System (IOOS) and its local Regional Associations–the Southern California Coastal Ocean Observing System (SCCOOS) and the Central and Northern California Ocean Observing System (CeNOOS). The state's action plan provides a concrete vision and set of trackable actions for making progress to better understanding and address critical threats to the productivity, ecology, and economic benefits derived from the state's coastal and nearshore marine ecosystems. In so doing, it serves as a model for other jurisdictions (national and subnational) seeking to act on ocean acidification.

The Action Plan outlines six strategies that map strategically with OA Alliance Call to Action (International Alliance to Combat Ocean Acidification, 2017):

Strategy 1 – Prepare for the Full Range of OA Risks and Impacts.
Strategy 2 – Activate Responsible Elements of State Government.
Strategy 3 – Reduce the Pollution that Causes OA.
Strategy 4 – Deploy Living Systems to Slow OA and Store Carbon.
Strategy 5 – Build Resilience of Affected Communities, Industries, and Interests.
Strategy 6 – Engage Beyond State Boundaries.

Actions proposed in the plan include, but are not limited to:

- Conduct a statewide vulnerability assessment to identify the risks OA poses to the California's biological resources, communities, and economies, within the context of other ongoing environmental changes and hazards, and to identify priorities and options for action to improve societal adaptive capacity.
- Design and make targeted investments in a monitoring and observation (M&O) system optimized to deliver decision-relevant information that serves user needs.
- Fully integrate OA into California state government policies, planning, and operations.
- Systematically integrate OA and coasts and oceans into California's GHG emissions reduction program.
- Implement a coordinated and strategic statewide approach to restoring, conserving and assisting in the migration of seagrass meadows, kelp forests, and salt marshes to achieve multiple state goals.

The scope of the action plan allows its application to be hyper-localized, regional, or even global– calling for specific inventory and prioritization of assets and actions across multiple scales. Capacity for demonstrative power and information exchange are also built into the process:

> *The primary purpose of this Action Plan is to provide a roadmap for the State of California to take tractable and strategic actions and make targeted investments to reduce and prepare for the impacts of OA. Although it focuses on California's particular needs and opportunities, these are cast within a regional, national, and international context, where appropriate, to achieve state goals, advance global efforts and collaboration, and help other jurisdictions move forward on this challenging problem." (Phillips et al., 2018).*

While this case study highlights California, there is similar progress in several states, which also benefit from synergies between regional and national partnerships. For instance, New York, an OA Alliance United States state member, along with Virginia and Hawaii, is making quick progress with the August 2018 announcement of State Ocean Acidification Task Force to evaluate impacts on the state's coastal waters and examine adaptive strategies. In this process, it will be essential that IOOS's Regional Associations there (Northeastern Regional Association and Coastal Ocean Observing System, NERACOOS, and Middle Atlantic Regional Association and Coastal Ocean Observing System, MARACOOS) and the associated Northeast Coastal Acidification Network (NECAN) and the Mid-Atlantic Coastal Acidification Network (MACAN) continue to build and maintain a network that helps inform policy makers and task force members charged with interpreting existing data and implementing further recommendations for investments and actions. Similar progress in other United States states has harnessed partnerships where Coastal Acidification Networks also in Alaska, the California Current, the Southeast, and Gulf bring together scientists, state and local agencies, tribes, and local stakeholders, working through the NOAA Ocean Acidification Program (OAP) and IOOS Regional Associations. Such efforts benefit from the specification of local needs and impacts that are relevant to the region, as well as from the consistency afforded through NOAA's OAP funding of observing efforts via the IOOS Regional Association assets.

DISCUSSION

Critical Elements in the Knowledge-to-Action Pipeline

The networks reviewed above are difficult to evaluate singly, as each activity builds on prior work. Cross-pollination is unavoidable, because some activities have been modeled directly on prior activities, while others have called on some of the same experts. Nevertheless, common themes re-appear in each activity, seeming to contribute to their success in driving forward stepwise action to address the impacts and causes of OA, building local communities committed to participating in a collective search for solutions, and creating sustained momentum at multiple organizational scales.

The collected examples here identify the elements of success that support the knowledge-to-action pipeline (**Figure 1**):

1) **Urgent need**. OA Action is strongly motivated by the need to protect and sustain marine resources that provide benefits to human communities, such as shellfish aquaculture industries or Arctic ecosystems.
2) **Interdisciplinary partnerships**. Bringing together a wide range of experts—not just on OA science, but also

on marine resource management, policy development, local industry needs, and community priorities—produces broader base of support and a more comprehensive set of solutions that are specifically tuned into community needs and priorities.

3) **Shared goals**. The interdisciplinary partnerships mentioned above have helped develop broad, collective visions of what OA preparation includes. Work has then commenced to pursue those goals via working groups, targeted activities, and more. Identifying and committing to these shared goals has also supported the development of stepwise action as well as activities that require long-term commitments (e.g., long-term monitoring or adaptation activities).
4) **Leveraging existing coordination structures**. With the existence of so many scientific and regional coordination bodies, it would be ineffective to set up several new OA coordination activities. As a result, the Pipeline has made wise use of existing networks, such as the IOOS regional associations and the Pacific Coast Collaborative, building out the number of networks only when necessary via activities such as the DFO-NOAA OA Coordination Committee and the OA Alliance.
5) **Communication**. It cannot be emphasized enough that regular, open communication has been critical to every element of the Pipeline described above. Creating trust among different stakeholder groups and developing a shared vision requires honest and wide-ranging discussions. Likewise, the commitment of assets to take action, as national and state governments are doing, requires negotiations and sometimes compromise to ensure equitable participation.

Obstructions in the Pipeline

Despite the progress made to date on converting OA knowledge to action, barriers to implementation still exist. Uncertainty is a primary obstacle, touching every element of the Pipeline, from the scientific understanding of OA, to responses of communities, effectiveness or feasibility of actions taken to address OA, and more. Prioritization of OA action is also a challenge given the multiple urgent competing priorities that leaders must consider. The feasibility of any action must be considered as well. Finally, the scalability of actions is also relatively untested and frequently not able to be clearly predicted.

Uncertainty

In addition to scientific uncertainty about how acidification affects marine resources and systems of interest (e.g., Kroeker et al., 2010), there is still a great deal of uncertainty surrounding the actions that can be taken to mitigate ocean acidification risks. Each intervention needs extensive testing to ensure it does in fact mitigate acidification or its impacts on the system of interest. Additionally, the economic cost and scalability of any intervention must be understood to provide a practical option for resource managers and industry leaders.

The most thoroughly tested set of interventions concern bivalve shellfish aquaculture. *In situ* monitoring and water chemistry amendments at shellfish hatcheries have been the focus of intensive study for nearly a decade (Barton et al., 2011, Barton et al., 2015) and can now be implemented at hatchery scale. In addition, co-culture of kelp and shellfish in aquaculture installations to decrease OA is being piloted in several locations. Phytoremediation research to support shellfish aquaculture focuses mainly on evaluating the appropriate physical setting for this type of intervention and other practical limits, like seasonal and economic limits.

Because of the uncertainty associated with impacts of ocean acidification on marine systems and the risk-to-reward balance of interventions, many groups are striving to promote proactive management rather than reactive management. While in some cases reactive management can be successful–consider the recovery of the Pacific Northwest shellfish hatcheries–chronic acidification, especially when combined with other stressors, may eventually be more difficult to manage. Preventing future impacts generally has a much lower economic cost than waiting for impacts to emerge, suffering the consequences, and attempting to both recover and mitigate future risk at the same time. Seung et al. (2015) used a bioeconomic model to compare proactive and reactive management to OA. According to their simulations, proactive management could maintain a sustainable crab fishery in Bristol Bay, Alaska. By contrast, a reactive management strategy led to the collapse of the crab population and closure of the fishery by mid- to late century. In Alaska the proactive viewpoint has been persuasive, helping to elevate the demand for action on acidification and yielding dedicated funding support for targeted fisheries management products.

Prioritization

For communities experiencing the impacts of climate change on multiple fronts, it can be difficult to demonstrate that acidification should be a priority. For communities along Alaska's northern coasts, through the Bering Sea and Bering Strait region, coastal erosion is an immediate and existential threat for some communities like Shishmaref. While ocean acidification may pose a threat to the ecosystem and subsistence assets these communities depend on, housing security is a much more urgent concern. Therefore there may be trade-offs to consider.

Reducing uncertainties around interventions' effectiveness, riskiness, and cost may help leaders make better decisions in light of competing priorities, as well as account for the political and economic dynamics which are most relevant to them (Cooley et al., 2016; Albright and Cooley, 2017). However, even when the community is united around ocean acidification risk, it can be difficult to balance the priorities of multiple stakeholders. Regions may also have to choose among vulnerable areas when deciding when and where to commit resources.

Feasibility

The best way to combat ocean acidification is by reducing CO_2 emissions. Numerous analyses showing that CO_2 emissions reduction will benefit the ocean have come from the scientific community in recent years (e.g., IPCC, 2014; Gattuso et al., 2015). However, large scale CO_2 emissions reductions have been slow materialize the international level. To help address this, the OA Alliance is attempting to consolidate the voices of leaders internationally calling for national and subnational governments to reduce emissions in order to slow the pace of ocean impacts and respond now to local climate related threats to ocean resources. This work is also connected to regional movements, which also benefit from smaller and localized actions–such as filling regional knowledge gaps in addition to making their own commitments to reducing CO_2 emissions. In these examples, the feasibility of different actions at different scales is factored into the recommendations for actions that are appropriate at each scale.

Scalability

Plans to address acidification within a particular region may not be applicable to other regions or across short and long time scales. Moreover, there are very few "complete" acidification stories that demonstrate the OA-related benefits of a particular action. Given that no single OA action plan can be considered a panacea, this increases the cost and the effort associated with the development of a local or regional OA adaptation plan, as a considerable amount of planning may be required. Organizations such as those reviewed here have helped share details of plans developed by one jurisdiction with others that wish to take action (In fact, this is one of the formal goals of the OA Alliance). In cases where plans developed by one region are applied elsewhere or over different time-scales, translation assistance is needed by OA experts. Precedent matters, especially for legislative actions concerning ocean acidification, and having evidence of success in one region may speed the adoption of actions in another region.

Looking Forward

In truth, combinations of actions and interventions are required, as there is no one-size-fits-all solution to address OA other than reducing global atmospheric CO_2 levels. Preserving the functions of ecosystems at risk from OA requires the application of an array of interventions, because not all interventions preserve all elements of an ecosystem (Albright and Cooley conference paper). Commitments to see interventions through to fruition must be secured early and sustained over time, as some actions take a much longer time than typical funding cycles or even political office terms (e.g., development of seasonal OA forecast model on West Coast has taken 10 years). This may require frank, difficult conversations about the priorities of leaders and communities, so they can seek to reconcile urgent, short-term needs with longer-term precautionary planning and development.

The key to overcoming all four of the challenges discussed above is increased communication and multi-disciplinary partnerships at the local, regional and international level. Creating networks that apply the best practices of the Pipeline can lead to rapid action on ocean acidification. Ongoing collaboration from the earliest research stages can help increase the likelihood that decision makers have the knowledge they need available in a useful and understandable format.

The positive impacts of the Pipeline have reached beyond the resource users and managers directly affected by OA. In a little more than 10 years, ocean acidification has matured from a niche issue recognized by a handful of academic and federal scientists to an issue discussed in mass market media and anticipated by marine resource users and managers, elected officials, and the public. This result has followed from a coordinated, concerted communication effort by the scientific community and advocacy organizations that was paired with intentional cultivation of partnerships among researchers and information users.

Bottom-up, self- or peer-organizing efforts have been extremely effective at engaging new constituencies and turning ocean acidification into a publicly recognized issue. Once citizens are informed and ready to act, they are among the most effective voices at getting decision makers to act as well. Not only will greater engagement by decision makers and elected leaders lead to more familiarity of the issue, it will also create a positive feedback in which solutions are ever more tuned to local needs and priorities.

CONCLUSION

While more remains to be known, it is becoming increasingly urgent that governments commit to taking action to address ocean acidification. Especially in light of the 2018 IPCC Special Report on Global Warming of 1.5°C, it is abundantly clear that local, regional and international efforts to reduce carbon dioxide emissions and adapt to unavoidable changes are essential to fully prepare for the impacts of a changing ocean.

Through such commitments, governments are more effectively able to unleash and direct much needed resources to reducing the sources of acidifying pollutants, to sharing information about the impacts of ocean acidification regionally, and to improving knowledge of how to adapt to unavoidable changes while building resilience in marine ecosystems.

In the future, the path connecting science to action will be increasingly well-trod by the OA community, as the topic continues to identify ecosystem impacts that will also impact human communities (Gattuso et al., 2015). Partnerships, such as those supported by NOAA, and external entities like the OA Alliance are creating networks among communities previously not connected. These entities are facilitating the development of climate resilience frameworks that help communities start the conversation about what elements of the future need to be planned for, and how governments can build upon existing structures and policies (e.g., CA OA action plan example).

Science is advancing and providing increasingly societally relevant answers: monitoring systems are widespread and growing, and our understanding of ecosystem impacts and the food web is also growing. The interaction of the two is being connected with new models such as ecosystem models and integrated assessment models. Questions relevant to decision-makers are increasingly being answered with these new model systems (e.g., Kaplan et al., 2010; Punt et al., 2014; Cooley et al., 2015; Siedlecki et al., 2016; Rheuban et al., 2018).

Continued effort on this front will be critical to engage support from decision-makers who fund the work, put it into use, and integrate it into the existing body of environmental management practices.

Working together we can we can increase global attention on actions that address the causes of ocean acidification and changing ocean conditions, as well as assist governments in establishing a set of actions that will reduce future impacts to our coastal communities, economies, and the health of our oceans. The knowledge-to-action Pipeline is a key component of this future vision.

AUTHOR CONTRIBUTIONS

JC provided the overall guidance and executive editing for the manuscript and wrote the sections introduction, discussion, and conclusion, contributed content to case studies, and designed the figures. All authors provided text input and editing. Content for section 1 was also provided by JN and TKl. JT led collaborative writing for sections 2.1, 2.4, and 3 with assistance from JN and TKl. AH led CAN representatives DD, KG, TKi, TKl, JoM, JaM, ELS, EO, GS, JV-D, and LW for section 2.2. HG-S developed section 2.3 with support from JC, CC, KA-S, EJ, DJ, and ES. SC contributed extensively to sections 2.4, 3, and led section 4.1.

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REFERENCES

Albright, R., and Cooley, S. (2017). "A solutions-based approach for coral reefs under OA: adaptation and mitigation," in *Proceedings of the Discussion paper for "Fourth International Workshop: Bridging the Gap between Ocean Acidification and Economic Valuation,"* 15-17 October 2017, (Monaco: Monaco Science Center), 40.

AMAP (2018). *AMAP Assessment 2018: Arctic Ocean Acidification*. Troms: Arctic Monitoring and Assessment Programme (AMAP), 187.

Barton, A., Hales, B., Waldbusser, G., Langdon, C., and Feely, R. A. (2011). The Pacific oyster, *Crassostrea gigas*, shows negative correlation to naturally elevated carbon dioxide levels: implications for near-term ocean acidification effects. *Limnol. Oceanogr.* 57, 698–710. doi: 10.4319/lo.2012.57.3.0698

Barton, A., Waldbusser, G. G., Feely, R. A., Weisberg, S. B., Newton, J. A., Hales, B., et al. (2015). Impacts of coastal acidification on the Pacific Northwest shellfish industry and adaptation strategies implemented in response. *Oceanography* 28, 146–159. doi: 10.5670/oceanog.2015.38

Chan, F., Boehm, A. B., Barth, J. A., Chornesky, E. A., Dickson, A. G., Feely, R. A., et al. (2016). *The West Coast Ocean Acidification and Hypoxia Science Panel: Major Findings, Recommendations, and Actions*. Oakland, CA: California Ocean Science Trust. doi: 10.5670/oceanog.2015.38

Cheung, W. W. L., Pinnegar, J., Merino, G., Jones, M. C., and Barange, M. (2012). Review of climate change impacts on marine fisheries in the U.K. and Ireland. *Aquat. Conserv.* 22, 368–388. doi: 10.1002/aqc.2248

Clements, J. C., and Chopin, T. (2016). Ocean acidification and marine aquaculture in North America: potential impacts and mitigation strategies. *Rev. Aquacult.* 9, 326–341. doi: 10.1111/raq/12140

Cooley, S. R., and Doney, S. C. (2009). Anticipating ocean acidification's economic consequences for commercial fisheries. *Environ Res Lett* 4: 024007. doi: 10.1088/1748-9326/4/2/024007

Cooley, S. R., Ono, C. R., Melcer, S., and Roberson, J. (2016). Community-level actions that can address ocean acidification. *Front. Mar. Sci.* 2:128. doi: 10.3389/fmars.2015.00128

Cooley, S. R., Rheuban, J. E., Hart, D. R., Luu, V., Glover, D. M., Hare, J. A., et al. (2015). An integrated assessment model for helping the United States sea scallop (*Placopecten magellanicus*) fishery plan ahead for ocean acidification and warming. *PLoS One* 10:e0124145. doi: 10.1371/journal.pone.0124145

Cottrell, R. S., Fleming, A., Fulton, E. A., Nash, K. L., Watson, R. A., and Blanchard, J. L. (2018). Considering land–sea interactions and trade-offs for food and biodiversity. *Glob. Chang. Biol.* 24, 580–596. doi: 10.1111/gcb.13873

Cross, J. N., Mathis, J. T., Pickart, R. S., and Bates, N. R. (2018). Formation and transport of corrosive water in the Pacific Arctic region. *Deep Sea Res. II* 152, 67–81. doi: 10.1016/j.dsr2.2018.05.020

Dupont, S., Hall, E., Calosi, P., and Lundve, B. (2014). *First Evidence of Altered Sensory Quality in a Shellfish Exposed to Decreased pH Relevant to Ocean Acidification*. Available at: https://bioone.org/journals/Journal-of-Shellfish-Research/volume-33/issue-3/035.033.0320/First-Evidence-of-Altered-Sensory-Quality-in-a-Shellfish-Exposed/10.2983/035.033.0320.full (accessed December 21, 2018).

Fabry, V. J., McClintock, J. B., Mathis, J. T., and Grebmeier, J. M. (2009). Ocean Acidification at high latitudes: the bellwether. *Oceanography* 22, 160–171. doi: 10.5670/oceanog.2009.105

Fabry, V. J., Seibel, B. A., Feely, R. A., and Orr, J. C. (2008). Impacts of ocean acidification on marine fauna and ecosystem processes. *ICES J. Mar. Sci.* 65, 414–432. doi: 10.1093/icesjms/fsn048

Feely, R. A., Klinger, T., Newton, J., and Chadsey, M. (2012). *Scientific summary of ocean acidification in Washington State Marine Waters*. NOAA ORR Special Report. Lacey, WA: Washington State Department of Ecology, 157.

Francis Pan, T. C., Applebaum, S. L., and Manahan, D. T. (2015). Experimental ocean acidification alters the allocation of metabolic energy. *Proc. Natl. Acad. Sci. U.S.A.* 112, 4696–4701. doi: 10.1073/pnas.1416967112

Garcia, S. M., and Rosenberg, A. A. (2010). Food security and marine capture fisheries: characteristics, trends, drivers, and future perspectives. *Philos. Trans. Royal. Soc. B* 365, 2869–2880. doi: 10.1098/rstb.2010.0171

Gattuso, J.-P., and Hansson, L. (2011). *Ocean Acidification*. New York, NY: Oxford University Press Inc., 408.

Gattuso, J.-P., Magnan, A., Bille, R., Cheung, W. W. L., Howes, E. L., Joos, F., et al. (2015). Contrasting futures for ocean and society from different anthropogenic CO_2 emissions scenarios. *Science* 349:aac4722. doi: 10.1126/science.aac4722

Gledhill, D. K., White, M. M., Salisbury, J., Thomas, H., Mlsna, I., Liebman, M., et al. (2015). Ocean and coastal acidification off New England and Nova Scotia. *Oceanography* 28, 182–197. doi: 10.5670/oceanog.2015.41

Guinotte, J. M., and Fabry, V. J. (2008). Ocean Acidification and its potential effects on marine ecosystems. *Ann. N. Y. Acad. Sci* 1134, 320–342. doi: 10.1196/annals.1439.013

Hoegh-Guldberg, O., Poloczanska, E. S., Skirving, W., and Dove, S. (2017). Coral reef ecosystems under climate change and ocean acidification. *Front. Mar. Sci.* 4:20. doi: 10.3389/fmars.2017.00158

Hughes, T. P., Barnes, M. L., Bellwood, D. R., Cinner, J. E., Cumming, G. S., Jackson, J. B. C., et al. (2017). Coral reefs in the Anthropocene. *Nature* 546, 82–90. doi: 10.1038/nature22901

International Alliance to Combat Ocean Acidification (2016). *The International Alliance to Combat Ocean Acidification: A Global Call to Action*. San Diego, CA: Founding Members of the International Alliance to Combat Ocean Acidification, 3.

International Alliance to Combat Ocean Acidification (2017). *The Action Toolkit: Building your Ocean Acidification Action Plan*. San Diego, CA: International Alliance to Combat Ocean Acidification, 7.

IPCC (2013). *Climate Change 2013: The Physical Science Basis. Contribution of Working group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignore, S. K. Allen, J. Boschung, et al. (Cambridge: Cambridge University Press), 1535. doi: 10.1017/CBO9781107415324

IPCC (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II, and III to the Fifth Assessment Report on the Intergovernmental Panel on Climate Change Core Writing Team*, eds R. K. Pachauri and L. A. Meyer (Geneva: IPCC), 151.

Jewett, L., DeGradpre, M., Graco, M., Tilbrook, B., Kapsenberg, L., Pelejero, C., et al. (2019). The global ocean acidification observing network: a worldwide collaborative approach to address ocean change serving science and society. *Front. Mar. Sci.*

Johnson, J., Bell, J., and Gupta, A. S. (2015). *Pacific Islands Ocean Acidification and Vulnerability Assessment. Apia, Samoa: Secretariat of the Pacific Regional Environment Program (SPREP)*. 41. Available at https://www.sprep.org/publications/pacific-islands-ocean-acidification-vulnerability-assessment (accessed December 21, 2018).

Kaplan, I. C., Levin, P. S., Burden, M., and Fulton, E. A. (2010). Fishing catch shares in the face of global change: a framework for integrating cumulative impacts and single-species management. *Can. J. Fish Aquat. Sci.* 67, 1968–1982. doi: 10.1139/F10-118

Kroeker, K. J., Kordas, R. L., Crim, R. N., and Singh, G. G. (2010). Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. *Ecol. Lett.* 13, 1419–1434. doi: 10.1111/j.1461-0248.2010.01518.x

Lam, V. W. Y., Cheung, W. W. L., and Sumalia, U. R. (2014). Marine capture fisheries in the Arctic: winners or losers under climate change and ocean acidification? *Fish and Fisheries* 17, 335–357. doi: 10.1111/faf.12106

Le Quéré, C., Mariarty, R., Andrew, R. M., Peterso, G. P., Clais, P., Friedlingstein, P., et al. (2014). Global carbon budget 2014. *Earth Syst. Sci. Data Discussions* 7, 521–610. doi: 10.5194/essdd-7-521-2014

Le Quesne, W. J. F., and Pinnegar, J. K. (2011). The potential impacts of ocean acidification: scaling from physiology to fisheries. *Fish and Fisheries* 13, 333–344. doi: 10.1111/j.1467-2979.2011.00423.x

Lemasson, A. J., Hall-Spencer, J. M., Kuri, V., and Knights, A. M. (2019). Changes in the biochemical and nutrient composition of seafood due to ocean acidification and warming. *Mar. Environ. Res.* 143, 82–92. doi: 10.1016/j.marenvres.2018.11.006

Long, W. C., Swiney, K. M., and Foy, R. J. (2013a). Effects of ocean acidification on the embryos and larvae of red king crab, *Paralithodes camtschaticus*. *Mar. Pollut. Bull.* 69, 38–47. doi: 10.1016/j.marpolbul.2013.01.011

Long, W. C., Swiney, K. M., Harris, C., Page, H. N., and Foy, R. S. (2013b). Effects of ocean acidification on juvenile red king crab (*Paralithodes camtschaticus*) and tanner crab (*Chionoecetes bairdi*) grwoth, condition, calcification, and survival. *PLoS One* 8:e60959. doi: 10.1371/journal.pone.0060959

Lynn, K., Daigle, J., Hoffman, J., Lake, F., Michelle, N., Ranco, D., et al. (2013). The impacts of climate change on tribal traditional foods. *Climat. Change* 120, 545–556. doi: 10.1007/s10583-013-0736-731

Marshall, K. N., Kaplan, I. C., Hodgson, E. E., Hermann, A., Busch, D. S., McElhany, P., et al. (2017). Risks of ocean acidification in the California Current food web and fisheries: ecosystem model projects. *Glob. Chang. Biol.* 23, 1525–1539. doi: 10.1111/gcb.13594

Mathis, J. T., Cooley, S. R., Lucey, N., Colt, S., Ekstrom, J., Hurst, T., et al. (2015). Ocean acidification risk assessment for Alaska's fishery sector. *Prog. Oceanogr.* 136, 71–91. doi: 10.1016/j.pocean.2014.07.001

McDowell Group (2017). *The Economic Value of Alaska's seafood Industry*. Anchorage, AK: McDowell Group. Available at: https://www.mcdowellgroup.net/wp-content/uploads/2017/10/ak-seafood-impacts-sep2017-final-digital-copy.pdf

Metcalf, V. (ed.) (2015). *A Business Plan for Sustainability. Alaska Eskimo Walrus Commission*. 25. Available at: http://eskimowalruscommission.org/wp-content/uploads/2016/01/FINAL-EWC-Business-Plan-1-6-16.pdf (accessed December 21, 2018).

Munday, P. L., Dixson, D. L., Donelson, J. M., Johnes, G. P., Pratchett, M. S., Devitsina, G. V., et al. (2009). Ocean acidification impairs olfactory discrimination and homing ability of a marine fish. *PNAS* 106, 1848–1852. doi: 10.1073/pnas.0809996106

Narita, D., Rehdanz, K., and Tol, R. S. J. (2012). Economic costs of ocean acidification: a look into the impacts on global shellfish production. *Climat. Change* 113, 1049–1063. doi: 10.1007/s10584-011-0383-383

National Marine Fisheries Service (2012). *Fisheries of the United States 2012*. Fisheries Statistics Division, National Oceanic and Atmospheric Administration, Report NO: 2012. Silver Spring, MD: National Marine Fisheries Service. doi: 10.1007/s10584-011-0383-3

Newton, J. A., Feely, R. A., Jewett, E. B., Williamson, P., and Mathis, J. T. (2015). *The Global Ocean Acidification Network: Requirements and Governance Plan*, Second Edn. Vienna: IAEA, 57.

Orr, J. C., Fabry, V. J., Aumont, O., Bopp, L., Doney, S. C., Feely, R. A., et al. (2005). Anthropogenic ocean acidification over the twenty-first century and its impacts on calcifying organisms. *Nature* 437, 681–686. doi: 10.1038/nature04095

Ou, M., Hamilton, T. J., Eom, J., Lyall, E. M., Gallup, J., Jiang, A., et al. (2015). Responses of pink salmon to CO_2-induced aquatic acidification. *Nat. Clim. Chang.* 5, 950–955. doi: 10.1038/nclimate2694

Phillips, J., Berry, W., Carter, H., Whiteman, L., and Chornesky, L. (eds) (2018). *State of California Ocean Acidification Action Plan*. San Diego, CA: California Ocean Protection Council. doi: 10.1038/nclimate2694

Pinnegar, J., Watt, T., and Kennedy, K. (2012). *CCRA Risk Assessment for the Marine and Fisheries Sector. UK* 2012 Climate Change Risk assessment. London: Department for Environment, Food and Rural Affairs,. doi: 10.1038/nclimate2694

Punt, A. E., Poljak, D., Dalton, M. G., and Foy, R. J. (2014). Evaluating the impact of ocean acidification on fishery yields and profits: the example of red king crab in Bristol Bay. *Ecol. Model.* 285, 39–53. doi: 10.1016/j.ecolmodel.2014.04.017

Rheuban, J. E., Doney, S. C., Cooley, S. R., and Hart, D. R. (2018). Projected impacts of future climate change, ocean acidification, and management of the US Atlantic sea scallop (*Placopecten magellanicus)* fishery. *PLoS One* 13:e0203536. doi: 10.1371/journal.pone.0203536

Richards, R. G., Davidson, A. T., Meynecke, J.-O., Beattie, K., Hernaman, V., Lynam, T., et al. (2015). Effects and mitigations of ocean acidification on wild aquaculture and prawn fisheries an Queensland, Australia. *Fish. Res.* 161, 42–56. doi: 10.1016/j.fishres.2014.06.013

Seung, C. K., Dalton, M. G., Punt, A. E., Poljak, D., and Foy, R. (2015). Economic impacts of changes in an Alaska crab fishery from ocean acidification. *Clim. Chang. Econ.* 6, 1–35. doi: 10.1142/S2010007815500177

Siedlecki, S. A., Kaplan, I. C., Hermann, A. J., Nguyen, T. T., Bond, N. A., Newton, J. A., et al. (2016). Experiments with seasonal forecasts of ocean conditions for the Northern region of the California Current upwelling system. *Nat. Sci. Rep.* 6:27203. doi: 10.1038/srep27203

Simpson, S. D., Munday, P. L., Wittenrich, M. L., Manassa, R., Dixson, D. L., Gagliano, M., et al. (2011). Ocean acidification erodes crucial auditory behavior in a marine fish. *Biol. Lett.* 7, 917–920. doi: 10.1098/rsbl.2011.0293

Speers, A. E., Besedin, E. Y., Parlardy, J. E., and Moore, C. (2016). Impacts of climate change and ocean acidification on coral reef fisheries: an integrated ecological-economic model. *Ecol. Econ.* 12, 33–43. doi: 10.1016/j.ecolecon.2016.04.012

Tilbrook, B., Jewett, E. B., DeGrandpre, M. D., Hernandez-Ayon, J. M., Feely, R. A., Gledhill, D. K., et al. (2019). An enhanced ocean acidification observing network: from people to technology to data synthesis and information exchange. *Front. Mar. Sci.* doi: 10.3389/fmars.2019.00337

Washington State Blue Ribbon Panel on Ocean Acidification (2012). "Ocean acidification: from knowledge to action," in *Washington State's Strategic Response*, eds H. Adelsman and L. W. Binder (Olympia, WA: Washington Department of Ecology), 158.

Washington State Blue Ribbon Panel on Ocean Acidification (2017). *An updated plan to address ocean acidification in Washington State*. Olympia, WA: Washington Department of Ecology.

Wassillie, K., and Poe, M. (2015). *Pacific Walrus and Coastal Alaska Native Subsistence Hunting: Considering Vulnerabilities from Ocean Acidification*. Piscataway, NJ: IEEE Earthzine.

Yañez, E., Lagos, N. A., Norambuena, R., Silva, C., Letelier, J., Much, K.-P., et al. (2017). "Impacts of climate change on marine fisheries and aquaculture in Chile," in *Climate Change Impacts on Fisheries and Aquaculture*, eds B. F. Phillips and M. Pérez-Ramírez (Hoboken, NJ: John Wiley and Sons, Ltd.), 239–332. doi: 10.1002/9781119154051.ch10

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An Integrated Approach to Coastal and Biological Observations

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Maritime economy, ecosystem-based management and climate change adaptation and mitigation raise emerging needs on coastal ocean and biological observations. Integrated ocean observing aims at optimizing sampling strategies and cost-efficiency, sharing data and best practices, and maximizing the value of the observations for multiple purposes. Recently developed cost-effective, near real time technology such as gliders, radars, ferrybox, and shallow water Argo floats, should be used operationally to generate operational coastal sea observations and analysis. Furthermore, value of disparate coastal ocean observations can be unlocked with multi-dimensional integration on fitness-for-the-purpose, parameter and instrumental. Integration of operational monitoring with offline monitoring programs, such as those for research, ecosystem-based management and commercial purposes, is necessary to fill the gaps. Such integration should lead to a system of networks which can deliver data for all kinds of purposes. Detailed integration activities are identified which should enhance the coastal ocean and biological observing capacity. Ultimately a program is required which integrates physical, biogeochemical and biological observation of the ocean, from coastal to deep-sea environments, bringing together global, regional, and local observation efforts.

Keywords: integrated observing, fit-for-purpose integration, parameter integration, instrumental integration, coastal observation, biological observation, ocean observation, coordinated observation

INTRODUCTION

The coastal ocean is the water body from the shelf-break to the shore, including estuary waters. Presently about 40% of the world's population live within 100 km of the coast. Anthropogenic activities within the watershed and the newly emerging maritime economy initiatives severely affect the coastal water. Monitoring of the coastal seas, therefore, becomes essential in providing marine information services for the maritime economy, for protection of marine environment and ecosystems and for climate change adaptation and mitigation. Coastal ocean observing has been developed in either national or regional level in the past decades, e.g., in Europe, United States, Australia, Japan, and China. Several papers or books discuss integrated and global observing systems (Malone and Cole, 2000; Babin et al., 2008; Liu et al., 2015). Early coastal monitoring components were designed to fit for specific purposes, e.g., operational applications, climate monitoring, environmental assessment, or fishery management. The monitoring activities were also carried out by different sectors with specific governmental mandates. In the last decade, integrated coastal ocean observing systems have been designed and developed to fit for multiple purposes. The US IOOS (Integrated Ocean Observing System) is a national observing infrastructure to cover the coastal shelf sea waters of the United States, managed by several regions. The IOOS was designed to provide data to support multi-purpose applications, ranging from operational services, climate change adaptation, maritime economy to ecosystem-based management, with a timely, operational data delivery (Corredor, 2018). In Australia, the Integrated Marine Observing System (IMOS, Hill et al., 2009) is similar to the United States system but was designed as a research infrastructure. Since major data streams of IMOS are delivered timely, they are also useful for operational forecasting and management of marine natural resources, etc. An important feature of both IOOS and IMOS is that they were built upon modern technologies e.g., gliders, high frequency radars, and animal borne instruments which have been identified as emerging technologies for future GOOS (Global Ocean Observing System) coastal and biological observing (Moltmann et al., 2019). In Europe, the European Regional Operational Oceanography Systems (ROOSs) also have integrated these technologies. In addition, ferrybox and shallow water Argo profilers are extensively used (She, 2018; Le-Traon et al., 2019). The ROOS observations were designed for operational oceanography, but can also be used for almost all other purposes, due to their operational online delivery, open and free access. There are significant efforts in integrating the ocean observing in the operational oceanography community. In the coastal ocean, the future integration aims to improve the cost-effectiveness and support the development of operational ecology (She et al., 2016) and seamless modeling (forecasting, reanalysis, and projection).

However, there are significant gaps in observations and cost-effectiveness in the existing online monitoring programs. On the other hand, there is already a significant amount of coastal and biological observations being collected for supporting ecosystem-based management and climate change adaptation and mitigation, as is coordinated by ICES (International Centre for Exploring the Sea) for fishery and regional conventions for environmental assessment in Europe and National Oceanic and Atmospheric Administration Fisheries in the United States. However, most of the data are delivered offline which do not fit the operational needs. There is an urgent need to integrate the online and offline monitoring programs to fill the observational and technological gaps. Instead of giving a comprehensive review of the existing coastal and biological observing, this paper aims at categorizing the "integrated observing" and how the existing gaps in coastal and biological observations can be filled through the integration. The integration discussed in this paper is at the scale of a regional sea basin, surrounded by one or more countries.

INTEGRATED COASTAL OCEAN OBSERVING

The integrated observing can be divided into three categories: fit-for-purpose integration, parameter integration, and instrumental integration, which addresses three stages of marine data value chain – observing, data management, and data usage. The fit-for-purpose integration is to integrate ocean observing from multiple sectors so that the observations can be measured for multiple purposes with improved data adequacy and cost-effectiveness. The parameter integration brings marine data of all parameters from air, water, biota, seabed to human activities together and makes them timely accessible. For the final data usage, the instrumental integration will produce the best monitoring products through integrating different monitoring components, e.g., *in situ* observations, remote sensing, and modeling. The three kinds of integration are illustrated in **Figure 1**. In order to maximize the value of the observing system, it is essential that the three kinds of integration are all addressed.

Fit-for-Purpose Integration

According to its purpose, ocean observing can be divided into governmental, research, and commercial activities. The governmental activity covers operational, environmental, fishery, and hydrological sectors. For a given sector, the observing is often coordinated at the regional sea scale via an "observational network" consisting of governmental agencies from different countries and/or regions, such as ROOSs and Northeast Pacific cooperation (Barth et al., 2019). Through enhanced coordination and integration among different governmental observing networks, research and commercial observing programs, the fit-for-purpose integration aims at filling the observation gaps and improving cost-effectiveness.

The multi-network integration can be implemented in three stages: first, a fit-for-purpose assessment on data adequacy, appropriateness, and cost-effectiveness of the existing observational networks has to be carried out to identify the gaps. In Europe, the data adequacy assessment has been carried out by the EMODnet (European Marine Observational Data network) Sea Basin Checkpoint projects for eleven social-benefit areas (Míguez et al., 2019). Second, the harmonized sampling scheme should be designed to fill the gaps for all purposes. For example, through improvement of near real time delivery of

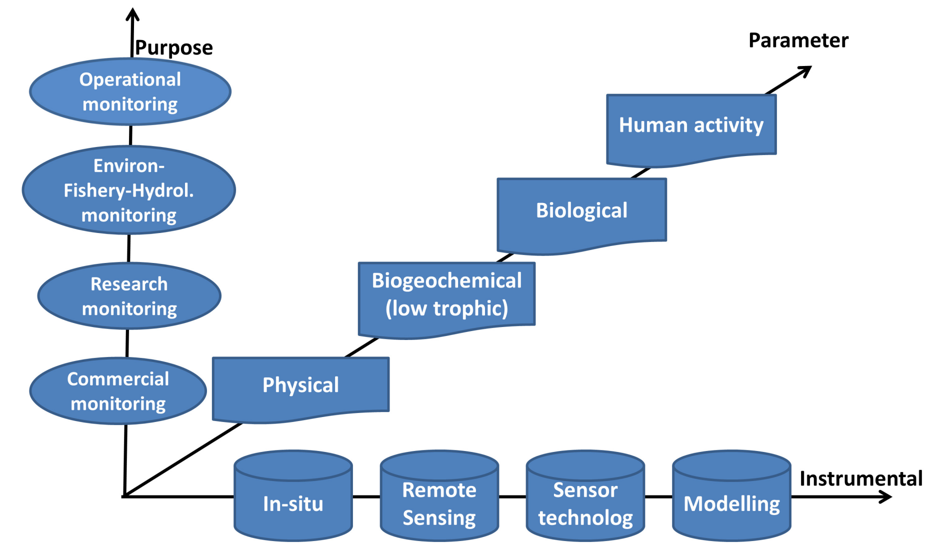

FIGURE 1 | Integrated observing – unlocking the value of ocean observing by integrating observations in three dimensions: fit-for-purpose, parameter, and instrumental.

ship observations from the offline monitoring programs, the data gaps for operational forecasting and interim reanalysis can be largely filled. However, the difficulty of harmonizing multi-networks should not be underestimated, in which significant institutional and community barriers should be overcome. The cost-effectiveness of the observing can be improved by optimal sampling strategy design, including cost-benefit analysis of the monitoring technology. Many sampling strategy design studies have been carried out, using methods ranging from statistical design e.g., Springtall and Meyers (1991), She et al. (2006), and Alvarez and Mourre (2012) to Observing System Simulation Experiments (OSSEs, Oke et al., 2015; She et al., 2017). However, these optimal sampling design studies were mainly dedicated for operational forecasting and reanalysis. Few of them have included cost-benefit analysis and fit-for-multi-purpose optimization. It should be noted that a significant amount of new knowledge and new observations will be needed for the optimization, which constitute the third stage of the implementation.

Parameter Integration

Fit-for-purpose integration improves observation adequacy, appropriateness, and cost-effectives. However, the required observations also have to be easily accessible by the users. In many cases, data exist but not available as they are managed by different sectorial data centers and also subjected to different data policies. This makes data sharing more difficult and data usage less efficient. Integration of marine observations across entire parameter spectrum can significantly improve the efficiency of the data use.

In Europe, the EMODnet (Míguez et al., this issue) is dedicated to integrate marine data across a full parameter spectrum – bathymetry, biology, chemistry, coastal mapping, geology, human activity, and physics. Recently emerging variables e.g., riverine inputs, underwater noise, sediment grain size, marine litter, and other datasets have been added in the portals. It was found, by the EMODnet Sea Basin Checkpoint projects, that the high integration level of marine data, such as done by EMODnet, has greatly facilitated the user applications and unlocks the value of observations.

Instrumental Integration

The value of observations can only be realized when they are used. *In situ* observing (including sensor technology and sampling schemes), remote sensing, and modeling are three ways of tracking ocean conditions. The instrumental integration means to produce needed products by integrating these three tools, e.g., data assimilation. Although such integration has been developed for decades, most of the operational assimilation just started in this century and mainly for open oceans and for physical variables. In Europe, the most well-known instrumental integration effort is Copernicus Marine Environment Monitoring Service (CMEMS, Le Traon et al., this issue). The lack of integration in coastal ocean and biogeochemical variables may be attributed to several reasons, e.g., lack of efficient schemes assimilating high frequency and multi-scale coastal observations, lack of skills in models to resolve fine scale features and biogeochemical processes and lack of qualified observations. These issues are major challenges in the instrumental integration of the coastal observing system, which should be resolved in the future.

BIOLOGICAL OBSERVATIONS

Biological ocean observations are any data collected in a systematic and regular basis which are based on living ocean inhabitants.

Multiple Disciplinary Coordination and Integration

Existing data currently supporting biodiversity assessments vary at a range of spatial and temporal scales, often severely limiting our capacity to understand the intensity, drivers and consequences of biodiversity change, and to assess the effectiveness of management measures. The availability of technology to enable more cost-effective collection of larger volumes of biological data is improving, such as Flowcam, but investment is needed to ensure that the most effective approaches are deployed widely and in a coordinated fashion.

Ultimately a program is required which integrates observation on physical, biogeochemical and biological aspects of ocean ecosystems and which establishes standardized approaches so that data can be shared, synthesized, analyzed, and interpreted from a large scale, long term, whole-system perspective. This has been identified as a priority for biological observations and operational ecology by the European Marine Board (Benedetti-Cecchi et al., 2018) and EuroGOOS (She et al., 2016). Ocean observation must be made across disciplines, as physical forces induce biological and chemical effects, which in turn mediate other (sometimes severe) biological changes, in some cases feeding back into physical changes. Comprehensive observing systems must be interoperable to enable studies across different science domains and observing regimes. A multidisciplinary approach where different science communities interact is necessary to provide a coherent, integrated view of the results. It is vital to bring together and connect the different marine and maritime stakeholders (from research to environmental monitoring and industry) collecting biological ocean observations to drive efficiency and cost-effectiveness.

Essential Ocean Variables (EOVs) and Essential Biodiversity Variables (EBVs)

A key step in developing a balanced and integrated program is the agreement of key variables on which to focus coordinated observation programs to inform on the status and trends of marine biodiversity. Two complementary frameworks are of note: GOOS (Global Ocean Observing System) EOVs and GEO BON EBVs. However, the EOVs and EBVs are a priorities list only and additional biological variables should be considered as needed. Biological EOVs and some of the marine EBVs are not new, but build on a long history of biological observations in the ocean. Several of them have been measured for decades worldwide and the availability of historical records is a key strength of the EOVs/EBVs.

There is still a clear challenge in reaching a threshold between overall scientific relevance, the needs for legislation without compromising the interoperability at global level, and the feasibility when defining the variables to be monitored. Thus, discussions and refinement of the two sets of essential variables are continuing and in 2016, the Marine Biodiversity Observation Network (MBON), the GOOS Biology and Ecosystems Panel, and the Ocean Biogeographic Information System (OBIS) signed an agreement to work together to enhance existing biological observation scopes and capacities, to implement best practices and international standards, and to encourage open access and data sharing. MBON and the GOOS BioEco Panel have developed the implementation of biological EOVs and marine EBVs and increased the number of monitoring programs that include these variables (Miloslavich et al., 2018; Muller-Karger et al., 2018).

Even though these variables are designed to be global, engaging regional systems such as the European Ocean Observation System (EOOS) will be key to ensuring progress and maturation.

Sustainability and Fitness to the Purpose

Biological ocean observation is very fragmented and, despite progress in storage and dissemination of digital information, there is still reluctance to share data within the scientific community and industry, and among national authorities. Programs tend to be driven by scientific interest or local needs. It is thus essential to establish appropriate mechanisms to overcome these barriers and improve data integration and networking.

In order to capture adequately the effects of global change on biodiversity, long term observations in key areas are required (generally involving many nations distributed across continents with a sustained long-term commitment toward observations). Almost none of the global observation networks has sustained or secured funding for their activities (Borja et al., 2016). For the system to be "fit for purpose" with maximum efficiency, observations must be harmonized using standard protocols, techniques and appropriate platforms contributing to a global observatory network. This ensures interoperability and comparability, which are important characteristics of any observing system.

Similar to those at the global scale, regional observing networks must be sustainable and adjustable to evolving observing requirements. Sustained long time series are of paramount importance and new observing approaches are emerging as technology progresses, making it possible to measure new parameters and/or improve existing protocols. New emerging techniques are often refined within SCOR working groups with suggestions for standardize use (e.g., WG154 and 156).

Most of the existing biological observing stations and platforms are operating at a local level (within a national sea area, or a given bay or stretch of coast within a national territory). These areas are characterized by high variability in terms of spatial and temporal resolution and are monitored often with infrequent and/or sporadic operations. Observation methods are usually specific to the needs for that specific area, either as variants of existing methods or completely new and locally developed. Local observing requirements may dictate specific approaches and techniques, ensuring a good "fit for purpose," but conformity to agreed standards both in terms of the quality of the observations and the data must be in place to ensure scalability and comparability.

The largest proportions of marine biological data available to scientists today are generated by short-term monitoring or research activities (such as the length of a Ph.D. program), which are organized regionally or locally. The lack of coordination and standardization in sampling and taxonomic identification techniques results in spatial and temporal gaps, that makes global scale synthesis extremely difficult.

To understand and manage global changes requires working across multiple geographical scales, which requires mechanisms for sharing expertise, protocols and data between and within scales. These mechanisms would help to minimize problems such as the general lack of and uneven distribution of taxonomic expertise among institutions and nations (Heip and McDonough, 2012). It is important to define and operate appropriate mechanisms tailored to the needs and characteristics of different scales as well as the links between them. Networking workshops for the definition of standards, inter-calibration exercises, labels of good practices and the exchange of staff are examples of such mechanisms.

DISCUSSION

This paper proposes an integrated approach for developing coastal and biological observing systems. Although the recently developed cost-effective, near real time technology such as gliders, radars, ferrybox, and shallow water Argo floats, can be used to generate operational coastal sea observations, integration with offline monitoring programs, such as those for research, ecosystem-based management and commercial purposes, is necessary to fill the gaps. Such integration should lead to a system of networks which can deliver data for all kinds of purposes.

For the ecosystem-based management, the space for integration is huge. For example, in Europe, Marine Strategy Framework Directive (MSFD) and Marine Spatial Planning Directive (MSPD), aiming at reaching Good Environmental Status (GES) and planning on sustainable of marine resources, will be implemented in the following decade by the EU Member States. As the implementation is at national level, each member state needs a comprehensive monitoring program which provides hydrography, biogeochemical, biodiversity observations, and also human activity data. These national monitoring programs can be harmonized at regional sea level, together with operational and research infrastructure to improve the cost-effectiveness. In order to effectively filling the gaps for the stakeholders, it is essential that the entire ocean observing value chain should be addressed with the three kinds of integration (fit-for-purpose, parameter, and instrumental).

It is also important to think how the integrated observing should be implemented. The three stages of integrated approach proposed in this paper can be used to fill the gaps. For the fit-for-purpose integration, coordinated observing for multiple observational networks can be a good start point. EOOS, as a future coordination framework of European ocean observing, has issued a call for action to the EU Member States: "*Countries should coordinate all national marine and coastal data collection efforts to improve efficiency, and identify priorities and gaps to meet policy and societal needs.*" (EOOS conference in November 21–23, 2018, Belgium, Brussels). It is expected that such basic integration of observations at national level will form a solid base for the fit-for-purpose integration. For the parameter integration, existing data policies should be further evolved to ensure open, free and timely access to government-funded observations, as well as engagement of research and commercial observations. Instrumental integration is currently significantly limited for the biogeochemical and biological variables: comparing to hydrographic variables, their observations are much sparser, models have much higher errors and species-dependent, and monitoring technologies also less efficient. New observations should be added with cost-effective sampling strategy. In addition, ecosystem models and innovative monitoring technologies should be further developed to facilitate the instrumental integration.

Based on the above discussion, a promising solution is to carry out an integrated observing program at regional sea level to fill the observational, technological and knowledge gaps by implementing all three kinds of integration.

Institutional barriers in different monitoring sectors, data management, and research communities are major obstacles when implementing the integration. Due to limit of space and extensive scope of the barriers, detailed analysis on the barriers is not given in this paper. We recommend readers to further specify the potential barriers in their own interested areas and systems. Timely delivery of biological observations is an important issue in developing operational ecology. It should be emphasized in the implementation of the three kinds of integration.

RECOMMENDATIONS

Support integrated observing for coastal and biological observations as an efficient way to unlock value of the ocean observations, and as a key component of GOOS, by developing a program which integrates observation on physical, biogeochemical and biological aspects of ocean ecosystems and which establishes standardized approaches so that data can be shared, synthesized, analyzed, and interpreted from a large scale, long term, whole-system perspective. Specific recommendations for the three kinds of integration are:

Fit-for-Purpose Integration

- Identify the observation and technology (cost-effectiveness) gaps via fit-for-purpose assessment.
- Harmonize ocean observing from fragmented purposes to make them suitable for multiple purposes, fill the observation gaps and improve cost-effectiveness by barrier-breaking, coordination, sampling design, and technology innovation.
- Sustain long time series observation and new emerging observing approaches as technology progresses, making it possible to measure new parameters and/or improve existing protocols.
- Fill observation and relevant knowledge gaps by implementing new, community observing capacities, e.g., through a sustained and cost-efficient research infrastructure at regional level.

- Contribute to a global observatory network, using standard protocols, techniques, and appropriate platforms, and ensuring quality, scalability, interoperability and comparability, especially for biological observing.

Parameter Integration

- Support parameter integration to deliver efficiently and timely marine observations in the entire spectrum of ocean variables and significantly improve the efficiency of the data use.
- Bring together and connect the different marine and maritime stakeholders (from research, operational service, environmental assessment to commercial activities), developing common data policy to engage data providers from different sectors for wider data access.
- Support integration initiatives, like the EMODnet, EOOS and the agreement between MBON, the GOOS Biology and Ecosystems Panel, and the OBIS; to facilitate user applications and unlock the value of observations.

Instrumental Integration

- Support instrumental integration to deliver the best monitoring products through integrating different monitoring components – *in situ*, satellite, and modeling.
- Filling knowledge gaps for the development of coastal and ecological services, e.g., biogeochemical and biological data assimilation, uncertainty in ecological models, optimal sampling design methodology.

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REFERENCES

Alvarez, A., and Mourre, B. (2012). Optimum sampling designs for a glider-mooring observing network. *J. Atmos. Ocean. Tech.* 4, 601–613. doi: 10.1175/JTECH-D-11-00105.1

Babin, M., Roesler, C. S., and Cullen, J. J. (eds) (2008). *Real-time Coastal Observing Systems for Marine Ecosystem Dynamics and Harmful Algal Blooms: Theory, Instrumentation and Modelling. Oceanographic Methodology Series*. Paris: UNESCO, 807.

Barth, J. A., Allen, S. E., Dever, E. P., Dewey, R. K., Evans, W., Feely, R. A., et al. (2019). Better regional ocean observing through cross-nation cooperation: a case study from the Northeast Pacific. *Front. Mar. Sci.* 6:93. doi: 10.3389/fmars.2019.00093

Benedetti-Cecchi, L., Crowe, T., Boehme, L., Boero, F., Christensen, A., Gremare, A., et al. (2018). "Strengthening Europe's Capability in Biological Ocean Observations," in *Future Science Brief* 3, eds A. Muniz Piniella, P. Kellett, K. Larkin, and J. J. Heymans (Ostend: European Marine Board), 76.

Borja, A., Elliott, M., Andersen, J. H., Berg, T., Carstensen, J., Halpern, B. S., et al. (2016). Overview of integrative assessment of marine systems: the ecosystem approach in practice. *Front. Mar. Sci.* 3:20. doi: 10.3389/fmars.2016.00020

Corredor, J. E. (2018). *Coastal Ocean Observing. Platforms, Sensors and Systems*. Berlin: Springer.

Heip, C., and McDonough, N. (2012). *Marine Biodiversity: A Science Roadmap for Europe*, Vol. 1. Ostend: European Marine Board.

Hill, K. L., Moltmann, T., Proctor, R., and Allen, S. (2009). Australia's integrated marine observing system. *Meteorol. Technol. Int.* 1, 114–120.

Le-Traon, P. Y., Reppucci, A., Fanjul, E. A., Aouf, L., Behrens, A., Belmonte, M., et al. (2019). From observation to information and users: the copernicus marine service perspective. *Front. Mar. Sci.* 6:234. doi: 10.3389/fmars.2019.00234

Liu, Y., Kerkering, H., and Weisberg, R. H. (eds) (2015). *Coastal Ocean Observing System*. Amsterdam: Elsevier.

Malone, T. C., and Cole, M. (2000). Toward a global scale coastal ocean observing system. *Oceanography* 13, 7–11. doi: 10.5670/oceanog.2000.48

Míguez, B. M., Novellino, A., Vinci, M., Claus, S., Calewaert, J.-B., Vallius, H., et al. (2019). The european marine observation and data network (EMODnet): visions and roles of the gateway to marine data in Europe. *Front. Mar. Sci.* doi: 10.5670/oceanog.2000.48

Miloslavich, P., Bax, N. J., Simmons, S. E., Klein, E., Appeltans, W., Aburto-Oropeza, O., et al. (2018). Essential ocean variables for global sustained observations of biodiversity and ecosystem changes. *Glob. Change Biol.* 24, 2416–2433. doi: 10.1111/gcb.14108

Moltmann, T., Turton, J., Zhang, H., Nolan, G., Gouldman, C., Griesbauer, L., et al. (2019). A global ocean observing system (GOOS), delivered through enhanced collaboration across regions, communities, and new technologies. *Front. Mar. Sci.* doi: 10.3389/fmars.2019.00291

Muller-Karger, F. E., Miloslavich, P., Bax, N., Simmons, S., Costello, M. J., Sousa Pinto, I., et al. (2018). Advancing marine biological observations by linking the essential ocean variables (EOVs) and essential biodiversity variables (EBVs) frameworks and data requirements. *Front. Mar. Sci.* 5:211. doi: 10.3389/fmars.2018.00211

Oke, P. R., Larnicol, G., Jones, E. M., Kourafalou, V. H., Sperrevik, A. K., Carse, F., et al. (2015). Assessing the impact of observations on ocean forecasts and reanalyses: Part 2: regional applications. *J. Oper. Oceanogr.* 8(Suppl. 1), s63–s79. doi: 10.1080/1755876x.2015.1022080

She, J. (2018). "Assessment of Baltic Sea observations for operational oceanography," in *Proceedings of the 8th EuroGOOS International Conference*, eds E. Buch, V. Fernández, D. Eparkhina, P. Gorringe, and G. Nolan (Bergen: EuroGOOS), 79–87.

She, J., Allen, I., Buch, E., Crise, A., Johannessen, J. A., Le Traon, P.-Y., et al. (2016). Developing european operational oceanography for blue growth, climate change adaptation and mitigation, and ecosystem-based management. *Ocean Sci.* 12, 953–976. doi: 10.5194/os-12-953-2016

She, J., Armstrup, B., Borenas, K., Buch, E., Funkquist, L., Luyten, P., et al. (2006). "ODON: optimal design of observational networks," in *Proceedings of the Scientific Report of EU Fifth Framework Project ODON (Optimal Design of Observational Networks)*, Belgium, 56.

She, J., Buch, E., and Nolan, G. (2017). *Report on Lessons Learned from OSSE Experiments in Support of the Definition of Requirements to an in-Situ Observing System. EuroGOOS-CMEMS report D2.4.1*. Bergen:EuroGOOS, 80.

Springtall, J., and Meyers, G. (1991). An optimal XBT sampling network for the eastern Pacific Ocean. *J. Geophys. Res.* 96, 10539–10552.

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REVIEW
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A Sustained Ocean Observing System in the Indian Ocean for Climate Related Scientific Knowledge and Societal Needs

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The Indian Ocean is warming faster than any of the global oceans and its climate is uniquely driven by the presence of a landmass at low latitudes, which causes monsoonal winds and reversing currents. The food, water, and energy security in the Indian Ocean rim countries and islands are intrinsically tied to its climate, with marine environmental goods and services, as well as trade within the basin, underpinning their economies. Hence, there are a range of societal needs for Indian Ocean observation arising from the influence of regional phenomena and climate change on, for instance, marine ecosystems, monsoon rains, and sea-level. The Indian Ocean Observing System (IndOOS), is a sustained observing system that monitors basin-scale ocean-atmosphere conditions, while providing flexibility in terms of emerging technologies and scientific and societal needs, and a framework for more regional and coastal monitoring. This paper reviews the societal and scientific motivations, current status, and future directions of IndOOS, while also discussing the need for enhanced coastal, shelf, and regional observations. The challenges of sustainability and implementation are also addressed, including capacity building, best practices, and integration of resources. The utility of IndOOS ultimately depends on the identification of, and engagement with, end-users and decision-makers and on the practical accessibility and transparency of data for a range of products and for decision-making processes. Therefore we highlight current progress, issues and challenges related to end user engagement with IndOOS, as well as the needs of the data assimilation and modeling communities. Knowledge of the status of the Indian Ocean climate and ecosystems and predictability of its future, depends on a wide range of socio-economic and environmental data, a significant part of which is provided by IndOOS.

Keywords: Indian Ocean, sustained observing system, IndOOS, data, end-user connections and applications, regional observing system, interdisciplinary, integration

OVERVIEW OF THE INDIAN OCEAN

Unique Features of the Indian Ocean

The Indian Ocean has many unique features, largely due to the vast Asian landmass to the north (**Figure 1**) and a low latitude throughflow from the Pacific via the Indonesian Seas (e.g., Gordon et al., 2010). The Asian monsoon winds drive a complete reversal of the currents north of 10°S (**Figure 1**) (e.g., Schott and McCreary, 2001), including the Somali Current at the western boundary and semi-annual jets (Wyrtki, 1973) along the equator. The strong southwest monsoon winds yield intense upwelling along the western boundary of the Arabian Sea during boreal summer (**Figure 1**), modulating evaporation and moisture transport toward India (Izumo et al., 2008), providing a globally significant source of atmospheric CO_2, and fostering intense oceanic productivity. This high productivity, together with low ventilation, leads to a subsurface depletion of oxygen (oxygen minimum zone, OMZ) that is now expanding and has already led to a dramatic shift in the Arabian Sea and Bay of Bengal ecosystem (Gomes et al., 2014; Bristow et al., 2017). Excess freshwater input from monsoon rain and river runoff generates strong saline stratification in the Bay of Bengal, inhibiting mixing and influencing oceanic productivity (Prasanna Kumar et al., 2002) and sea surface temperature (SST), which in turn regulate regional climate (Shenoi et al., 2002) and weather extremes (Neetu et al., 2019).

The Indian Ocean receives excess heat from the atmosphere and via the Indonesian Throughflow (ITF; Sprintall et al., 2014) and this is exported to the Atlantic and Southern Oceans via an ocean gyre circulation and an upper-ocean overturning cell (Ganachaud and Wunsch, 2000; Lumpkin and Speer, 2007;

Abbreviations: ADCP, Acoustic Doppler Current Profiler; AIC, Argo Information Center; ARGO, global array of temperature/salinity profiling floats; ASCA, Agulhas System Climate Array; BGC, biogeochemical; BMKG, Indonesian Agency for Meteorology, Climatology and Geophysics; BoB, Bay of Bengal; BoM, Bureau of Meteorology; BP-GEO, Blue Planet-Group on Earth Observations; CEOS, Committee on Earth Observation Satellites; CGCM, Coupled General Circulation Model; CFS, Climate Forecast System; Chl, chlorophyll; CINDY, Cooperative Indian Ocean Experiment on Intraseasonal Variability; CLIVAR, Climate and Ocean: Variability, Predictability and Change; CPC, Climate Prediction Center; CPIES, Current and pressure-sensor-equipped Inverted Echo Sounder; CTD, conductivity, temperature, and depth; DBCP, Data Buoy Cooperation Panel, JCOMM; DMI, Dipole Mode Index; DO, dissolved oxygen; DYNAMO, dynamics of the MJO field campaign; EEZ, exclusive economic zone; ENSO, El Niño-Southern Oscillation; EOVs, essential ocean variables; FDES, Framework for Development of Environment Statistics; FOO, Framework for Ocean Observing; GCM, general circulation model; GDP, Global Drifter Program; GEO, Group on Earth Observations; GLOSS, Global Sea Level Observing System; GO-SHIP, Global Ocean Ship-Based Hydrographic Investigations Program; GODAE, Global Ocean Data Assimilation Experiment; GOOS, Global Ocean Observing System; GTMBA, Global Tropical Moored Buoy Array; GTS, Global Telecommunication System; IIOE-2, Second International Indian Ocean Expedition; IMOS, Integrated Marine Observing System; IndOOS, Indian Ocean Observing System; IOBM, Indian Ocean Basin Mode; IOC, Intergovernmental Oceanographic Commission; IOCINDIO, IOC Regional Committee for the Central Indian Ocean; IOD, Indian Ocean Dipole; IODE, International Oceanographic Data Exchange; IO-GOOS, Indian Ocean component of the Global Ocean Observing System; IORA, Indian Ocean Rim Association; IORP, Indian Ocean Regional Panel; IPCC, Intergovernmental Panel on Climate Change; IRD, Institut de Recherche pour le Développement; IRF, IndOOS Resources Forum; ITF, Indonesian Throughflow; JAMSTEC, Japan Agency for Marine-Earth Science and Technology; JCOMM, Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology; JCOMMOPS, Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology *in situ* Observing Programs Support Centre; LH, latent heat; LW, longwave; MISO, monsoon intra-seasonal oscillation; MoES, Ministry of Earth Sciences; MJO, Madden–Julian Oscillation; NCEP, National Center for Environmental Prediction, NOAA; NOAA, National Oceanic and Atmospheric Administration; ORA-IP, Ocean Reanalysis Intercomparison Project; ODA, ocean data assimilation; OECD, Organization for Economic Co-operation and Development; OMNI, Ocean Moored Buoy Network; OMZ, oxygen minimum zone; OPS, Observation Program Support; OSSE, observing system simulation experiments; PANGEA, Partnerships for New GEOSS (Global Earth Observing System of Systems) Applications; PMEL, Pacific Marine Environmental Laboratory; RAMA, Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction; S2S, Subseasonal-to-seasonal; SCSIO, South China Sea Institute of Oceanology; SDGs, sustainable development goals; SEEA, System for Environmental Economic Accounting; SH, sensible heat; SIBER, Sustained Indian Ocean Biogeochemistry and Ecosystem Research; SIOD, Subtropical Indian Ocean Dipole; SNA, System of National Accounts; SST, sea surface temperature; STD, standard deviation; SW, shortwave; TIP, Tropical Moored Buoy Implementation Panel; TSFS, Timor Sea Flux Station; UN, United Nations; UNFCCC, United Nations Framework Convention on Climate Change; UNESCO, United Nations Educational, Scientific and Cultural Organization; WCRP, World Climate Research Programme; WESTPAC, IOC Sub-Commission for the Western Pacific; WMO, World Meteorological Organization; XBT, eXpendable Bathy Thermograph.

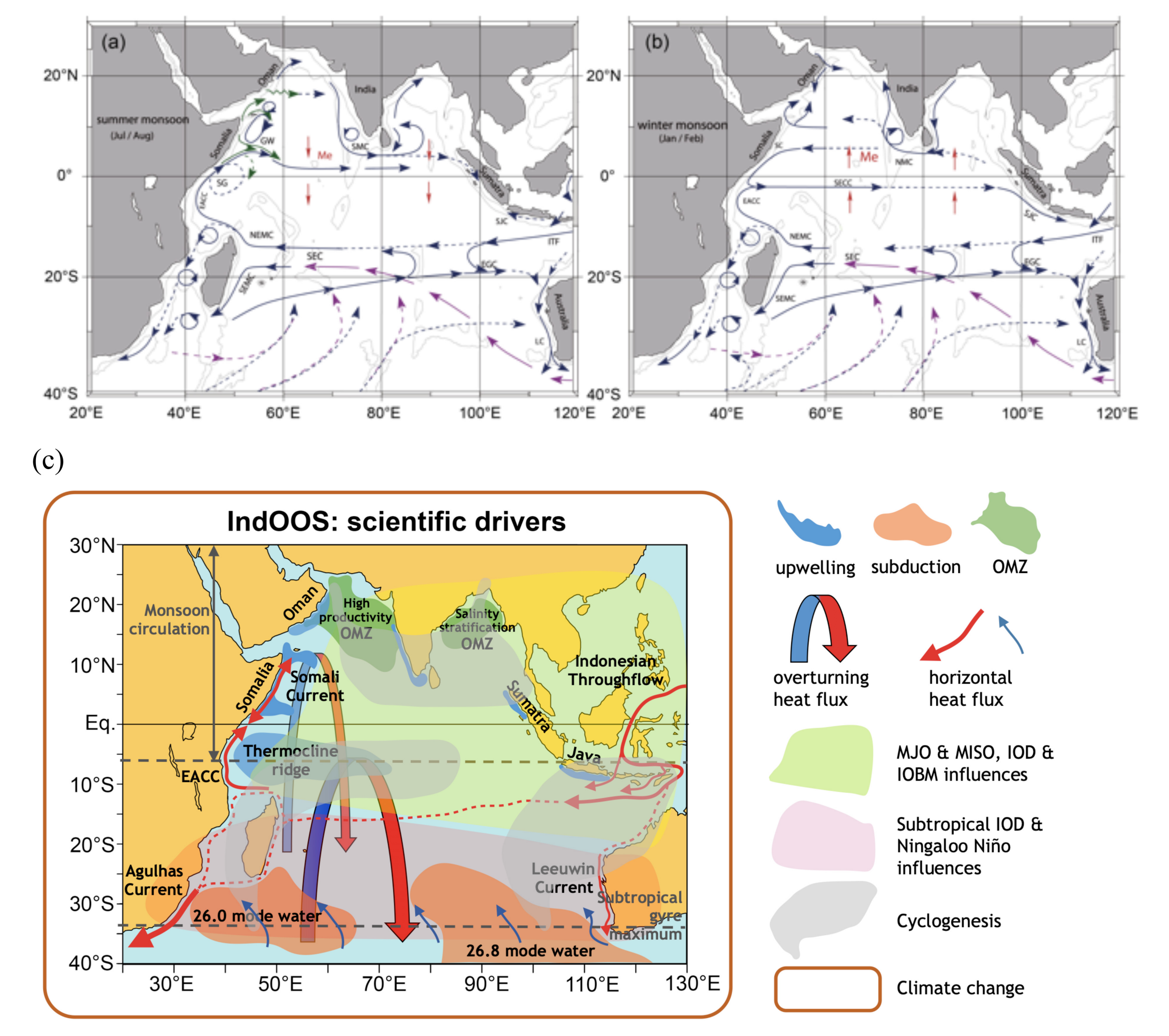

FIGURE 1 | Indian Ocean basin circulations during **(a)** boreal summer monsoon and **(b)** boreal winter monsoon (Schott et al., 2009). **(c)** Schematic view of key phenomena in the Indian Ocean (from the IndOOS decadal review led by IORP, to be published in 2019).

Hernández-Guerra and Talley, 2016), which are thought to be strongly constrained by the Agulhas Current at the western boundary (Bryden and Beal, 2001).

A large part of the low latitude Indian Ocean is covered by surface water warmer than 28°C, where deep atmospheric convection is maintained (e.g., Graham and Barnett, 1987) and the global atmospheric circulation cell, the Walker Circulation, is energized. Deep atmospheric convection is modulated by the Madden–Julian Oscillation (MJO) and by the monsoon intraseasonal oscillation (MISO), which induce subseasonal air–sea interactions (DeMott et al., 2015). The western tropical Indian Ocean, around 5–10°S, is a particularly important region for air–sea coupling. The thermocline ridge (**Figure 1**), associated with off-equatorial upwelling of the shallow overturning circulation, makes the SST there highly sensitive to atmospheric anomalies, which in turn impact the cyclogenesis and MJO development (e.g., Vialard et al., 2009).

At interannual time scales, the tropical Indian Ocean exhibits uniform warming during and after El Niño events (e.g., Xie et al., 2009), a response known as the Indian Ocean Basin Mode (IOBM). The Indian Ocean also has important interannual climate modes of its own, such as the Indian Ocean Dipole (IOD; Saji et al., 1999; Webster et al., 1999). In its positive phase, cold SSTs near Java-Sumatra, warm temperatures in the western tropical Indian Ocean thermocline ridge, and anomalous easterly winds near the equator induce various impacts like droughts in Indonesia and Australia and floods over eastern Africa (e.g., Yamagata et al., 2004). The Indian Ocean is also home to subtropical climate modes, such as the Subtropical Indian Ocean Dipole (SIOD) which manifests as large-scale SST anomalies spanning 15–45°S, with strong influence on South African rainfall (Reason, 2001).

The Indian Ocean is the only ocean with a poleward flowing boundary current on the eastern side of a subtropical gyre – the Leeuwin Current off Western Australia – giving rise to a unique ecology (Waite et al., 2007). Climate variability develops under the form of Ningaloo Niño events, intense marine heatwaves, which affect local fisheries and rainfall over neighboring Western Australia (Feng et al., 2013, 2015).

Due to paucity of observations, little is known about the decadal variations in the Indian Ocean (Han et al., 2014), which makes it difficult to distinguish climate change trends from patterns of natural variability (e.g., Carson et al., 2015). Even less is known about the changing biogeochemistry and higher trophic levels of the Indian Ocean at these time scales (Singh and Ramesh, 2015). There is, however, no doubt that the Indian Ocean is responding to anthropogenic climate change, with evidence of increasing SSTs and heat content, rising sea level, increased carbon and nitrogen uptake, and an intensified water cycle (Intergovernmental Panel on Climate Change [IPCC], 2013; Han et al., 2014; Kumar et al., 2018).

Societal Needs for Observing Systems

The Indian Ocean basin is surrounded by 22 countries, which contain almost one third of mankind, many of which are vulnerable to extreme weather events and climate change. These rim countries depend on rain-fed agriculture, which is tightly linked to monsoon rainfall. Indian Ocean SSTs have been shown to influence these monsoon rains, as well as flooding in east African countries (Saji et al., 1999; Webster et al., 1999; Roxy et al., 2016), and droughts and wildfires in Indonesia (Abram et al., 2003; D'Arrigo and Wilson, 2008) and Australia (Ashok et al., 2003; Ummenhofer et al., 2009).

Although the Indian Ocean is the smallest of the world's major oceans, it has accounted for more than one quarter of global ocean heat gain over the last 20 years (Lee et al., 2015; Cheng et al., 2016) and perhaps as much as 45% over the upper 700 m in the last 10 years (Desbruyères et al., 2017). This rapid warming (Roxy et al., 2016) is linked to decreasing rainfall over eastern Africa, which is predicted to increase the number of undernourished people in this region by 50% by 2030 (Funk et al., 2008).

Oceanic heat content and its distribution also influences winds, rainfall, storm intensity, and sea level rise (Han et al., 2014) and can influence fisheries and marine ecosystems due to associated changes in stratification, oxygen, and nutrient levels (Roxy et al., 2016). Many of the rim countries depend on fisheries for their livelihood, but the intense marine productivity is highly vulnerable to projected climate change (Allison et al., 2009; Kaur-Kahlon et al., 2016; Roxy et al., 2016; Kumar et al., 2018), such as changes in the monsoon winds and hence upwelling, as well as the expanding OMZ (e.g., Naqvi et al., 2010).

Beyond its direct impact on rim countries, the Indian Ocean influences climate globally. The basin accounts for about one fifth of the global oceanic uptake of anthropogenic CO_2 (Takahashi et al., 2002), helping to buffer the effects of global warming. It is the breeding ground for the MJO, which modulates rainfall and tropical cyclone activity across most of the tropics (Zhang, 2005). In addition to this, year to year temperature variations associated with the Indian Ocean influence the evolution of the El Niño Southern Oscillation (ENSO) in the Pacific Ocean (e.g., Clarke and Van Gorder, 2003; Izumo et al., 2010; Luo et al., 2010; Terray et al., 2015).

The Indian Ocean is also a tropical-subtropical gateway from the Pacific to the Atlantic Ocean, as part of the global "conveyor belt" (Broecker, 1991), regulating and redistributing heat within the global ocean. The Indian Ocean surface warming trend has far reaching impacts, modulating Pacific (e.g., Luo et al., 2012; Hamlington et al., 2014; Han et al., 2014; Dong and McPhaden, 2017; Cai et al., 2019) and North Atlantic climate (e.g., Hoerling et al., 2004) and causing droughts in the West Sahel and Mediterranean (e.g., Giannini et al., 2003; Hoerling et al., 2012).

Indian Ocean Observing System (IndOOS)

Indian Ocean Observing System emerged from discussions at the first OceanObs meeting in 1999, a time of new and advancing observing technologies, such as profiling floats (Argo), satellite missions, and surface meteorological buoys. Based on scientific and societal needs, an implementation plan for IndOOS was put together by the Indian Ocean Panel (now the Indian Ocean Regional Panel, IORP) in 2006, established under the Climate and Ocean Variability, Predictability, and Change (CLIVAR) and Global Ocean Observing System (GOOS) programs. The goal of IndOOS is to provide sustained high-quality oceanographic and marine meteorological measurements to support knowledge based decision-making through improved scientific understanding, weather and climate forecasts, and environmental assessments for the benefit of society. Observing system simulation experiments (OSSE) for the moored array, the Argo network, and the eXpendable Bathy Thermograph (XBT) network were conducted for the original IndOOS design (Ballabrera-Poy et al., 2007; Oke and Schiller, 2007; Vecchi and Harrison, 2007), providing justifications for measurement locations and sampling frequency.

A few years later, in a white paper for OceanObs'09, Masumoto et al. (2010) noted two priorities for IndOOS: Completion of the moored tropical array (Research Moored Array for African-Asian-Australian Monsoon Analysis and prediction, RAMA), which was then 47% complete, and attainment of the necessary resources to sustain IndOOS. Other noted needs were to improve coordination across platforms and regional and basin scale programs, improve data and product distribution, and enhance capacity development in Indian Ocean rim countries. As a result of these recommendations the IndOOS Resources Forum (IRF) and Sustained Indian Ocean Biogeochemistry and Ecosystem Research (SIBER) panel were formed.

Current State of IndOOS

IndOOS (**Figure 2a**) comprises of five *in situ* observing networks: RAMA, profiling floats (Argo program), surface drifters (Global Drifter Program, GDP), repeat temperature lines (XBT network), and tide gauges. Augmenting these networks are remotely sensed observations of surface winds, sea level, SST and salinity, rainfall, and ocean color, as well as a coarse network of decadal hydrographic survey lines (The Global Ocean Ship-Based Hydrographic Investigations Program, GO-SHIP).

RAMA is a centerpiece of the observing network (McPhaden et al., 2009) and followed early pilot programs by Japan and India to deploy current meter moorings along the equator. Thereafter, United States, Indonesia, China, Australia, and the United Nations, through two international large marine ecosystem programs (Agulhas Somali Large Marine Ecosystem and Bay of Bengal Large Marine Ecosystem), have jointly implemented and maintained RAMA. As part of a recent decadal review of the IndOOS, the array has been redesigned (RAMA-2.0) and is now 91% complete (c.f., **Figures 2a,b**), with the establishment of new sites in the Arabian Sea under United States–India collaboration. Efforts are also underway to integrate within the RAMA framework an additional eight Indian moorings of the Ocean Moored Buoy Network (OMNI) that are outside the Indian exclusive economic zone (EEZ). RAMA provides hourly and daily averaged time series of key oceanographic and surface meteorological variables in real-time[1]. These measurements help us understand the broad range of times scales, from diurnal to decadal, that affect weather and climate variability and are especially valuable for studies of ocean–atmosphere interactions associated with the MJO and MISO. Data from the RAMA moorings are made available to operational weather and climate prediction centers around the world through the Global Telecommunications System (GTS), providing essential input for weather and seasonal forecast models.

The Argo network is global (Gould et al., 2004), consisting of one autonomous profiler per 3° × 3° region, each profiling the ocean (temperature, salinity, and pressure) down to 2000 m every 10 days. Design coverage is 450 floats in the Indian Ocean north of 40°S and was first achieved in 2008. Argo has become the primary data source for understanding variability and trends within the ocean, such as the increase in ocean heat content and the persistence of marine heat waves – phenomena which satellite or other observational platforms are unable to capture. Argo data are used for operational oceanography, for validating and initializing ocean and climate models and are assimilated into regional and global models (such as Global Ocean Data Assimilation System). Since 2016, a growing number of profilers (currently 48) are equipped with biogeochemical sensors to measure key processes related to plankton blooms, OMZs, and fisheries.

The XBT network predates Argo and is operated by voluntary observing ships, which collect temperature observations over the upper ∼800 m of the ocean along regular commercial shipping routes. Parts of the XBT network remain important for monitoring phenomena poorly sampled by Argo, such as

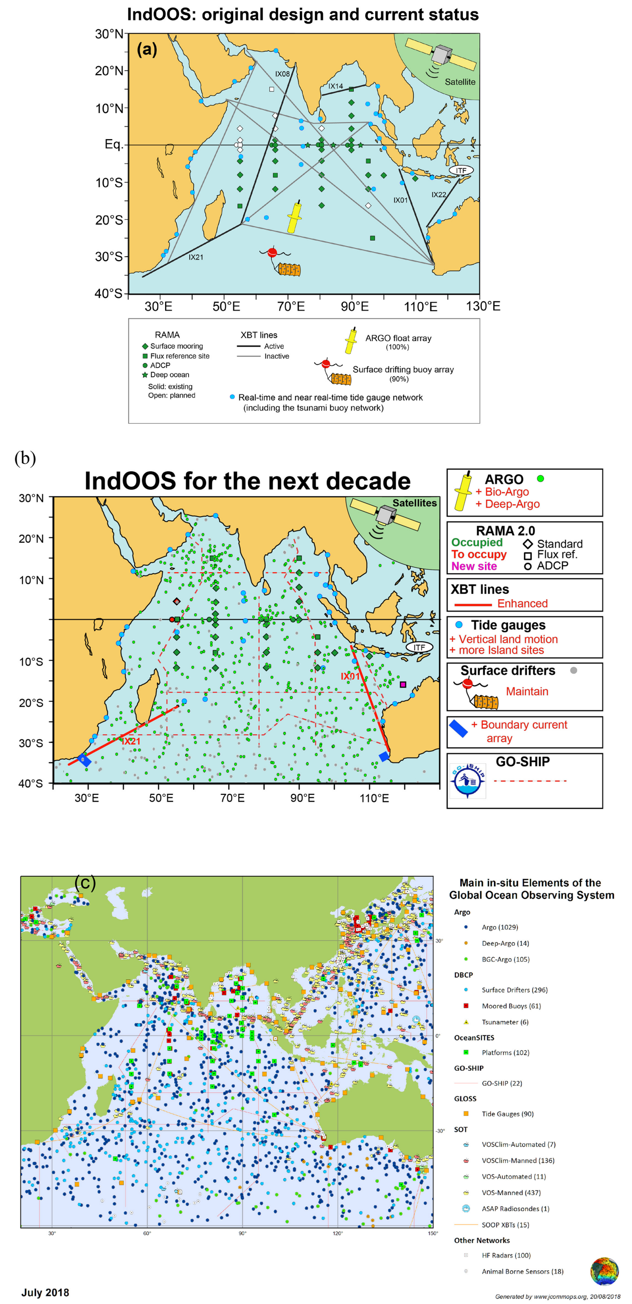

FIGURE 2 | (a) IndOOS original design and current status. The original IndOOS design comprises the RAMA, Argo, XBT network, surface drifting buoys, and tide gauge components. **(b)** The proposed evolution of IndOOS (from the IndOOS decadal review led by IORP, to be published in 2019). **(c)** Current state of IndOOS, as on July 2018 (from JCOMM OPS webpage at http://www.jcommops.org/board. Note that the numbers indicated includes the buoys and floats not only in the Indian Ocean but also in the South China Sea and a part of the western Pacific Ocean).

boundary currents and oceanic fronts, mesoscale variability, and volume and heat transports. The IX01 XBT line between Indonesia and Australia (**Figure 2a**) is a critical example through which the interannual-to-decadal variability of the ITF has been

[1]https://www.pmel.noaa.gov/tao/drupal/disdel/

quantified (Meyers et al., 1995; Sprintall et al., 2002; Wijffels et al., 2008), as well as the large heat transfer from the Pacific to the Indian Ocean over the last two decades (Lee et al., 2015).

The GDP consists of surface drifters drogued at 15 m depth to follow ocean currents at a density of one drifter per 5° × 5° region. All drifters also measure temperature and about half now measure sea level pressure, which has significantly improved numerical weather prediction (Centurioni et al., 2016). Among other important advances, surface drifters have allowed derivation of absolute surface geostrophic velocities from satellite altimeter (Maximenko et al., 2009), as well as the seasonal mapping of the reversing monsoon circulation in the Arabian Sea (Beal et al., 2013).

The tide-gauge network around the Indian Ocean rim provides vital *in situ* measurements of sea-level which are needed for the detection of tsunamis and cyclone-induced storm surges, as well as the prediction of tides. Tide-gauge data are also used for understanding of basin-scale variability and trends in sea-level rise, and providing *in situ* validation data for sea level data from satellites. Dynamical changes associated with coastally trapped waves (Iskandar et al., 2005) and the Pacific inflow along the west coast of Australia (Feng et al., 2004) are also detected with tide gauges. Importantly, land motion is measured at a subset of tide gauge stations to monitor the subsidence or emergence levels of the land, information necessary for the precise quantification of long-term trends in sea level.

The observing networks that make up IndOOS are most effective when combined together and used with other vital observing programs, such as global satellite missions and the decadal, multi-disciplinary, hydrographic surveys of GO-SHIP as well as more regional observing systems. For example, GO-SHIP provides calibrations for salinity and oxygen that are pivotal pivotal in maintaining Argo measurement accuracy for detection of long-term changes; samples beneath 2000 m depth, the maximum profiling depth of Argo floats and collects a suite of biogeochemical profiles as yet unobtainable via Argo.

IndOOS Decadal Review Report and Its Relation to This White Paper

Starting from the first workshop in January 2017 in Perth Australia, the decadal review of the IndOOS is near completion. The review has been led by the CLIVAR/IOC/GOOS IORP and aims at presenting a community consensus of actionable and justifiable recommendations for sustaining and enhancing a fit-for-purpose observing system for the next decade.

As an example, several recommendations were made specific to RAMA, including a reduction of the array to from 46 to 33 moorings, by removing sites that suffered poor data-return due to lack of ship time or vandalism and at the same time an enhancement of upper-ocean measurements at key sites in the array to capture diurnal signals that affect subseasonal-to-seasonal predictability of MJO and MISO development. The updated array, referred to as RAMA-2.0 (**Figure 2b**) will be more robust, capable, and cost-effective. This exercise is a good example of how observing systems need to be evolved based on readiness, new scientific understanding, feedback from data users and societal needs, as developed by the Framework for Ocean Observing (FOO) that was established as a key outcome from the previous OceanObs'09 meeting (Task Team for an Integrated Framework for Sustained Ocean Observing, 2012).

In this community white paper, while we highlight many of the findings from the IndOOS review, we also develop discussion on broader topics, such as the need for more coastal, shelf, and regional observations and the implementation challenges of these. Therefore, the IndOOS decadal review and this white paper are complementary in addressing the future directions of IndOOS over the coming decade.

FROM OBSERVATIONS TO PRODUCTS AND SERVICES

What Does the Satellite Flux Analysis/State Estimation/Re-analyses Community Need From IndOOS?

Significant progress has been made in improving surface flux estimations in recent decades. Yet, balancing the heat and freshwater budgets at the ocean surface from satellite and re-analyses flux products remains challenging (Yu, 2019). Uncertainties in flux products are large, particularly in the tropical oceans. The lack of representation of tropical convective clouds in atmospheric re-analyses models affects the surface radiative budget, leading to major errors in the net heat balance in the deep convective regime. In **Figure 3**, uncertainties are most pronounced in the Indo-Pacific warm pool/deep convection region, with uncertainty in net radiation (SW-LW) dominating over the uncertainty in latent and sensible heat. The standard deviation (STD) difference in mean SW-LW products is 15–20 Wm^{-2}, which is greater than the entire annual-mean net heat input into the Indian Ocean.

The meteorological and flux measurements from the RAMA moored buoy array are essential to improving these surface flux products. They serve as benchmark time series to help diagnose the problems in surface radiation and turbulent flux estimates and guide improvements in re-analyses models. Air–sea measurements using autonomous surface platforms, such as drifters, wavegliders, and saildrones, have advanced rapidly in recent years and are able to sample more regions and phenomena. Sustained observations capacities of such instruments need to be tested in the framework of process studies, an example is the persistent sampling of multiscale air–sea processes under extreme weather events. Future surface flux estimates, particularly in the deep convective regime associated with the Indo-Pacific warm pool, will benefit tremendously from the scientific and operational achievements made by the autonomous surface platforms.

IndOOS observations also provide critical data to evaluate and constrain ocean data assimilation (ODA) or ocean re-analyses products, which are crucial for estimations of decadal and long-term trends. In particular, RAMA and Argo are the backbone

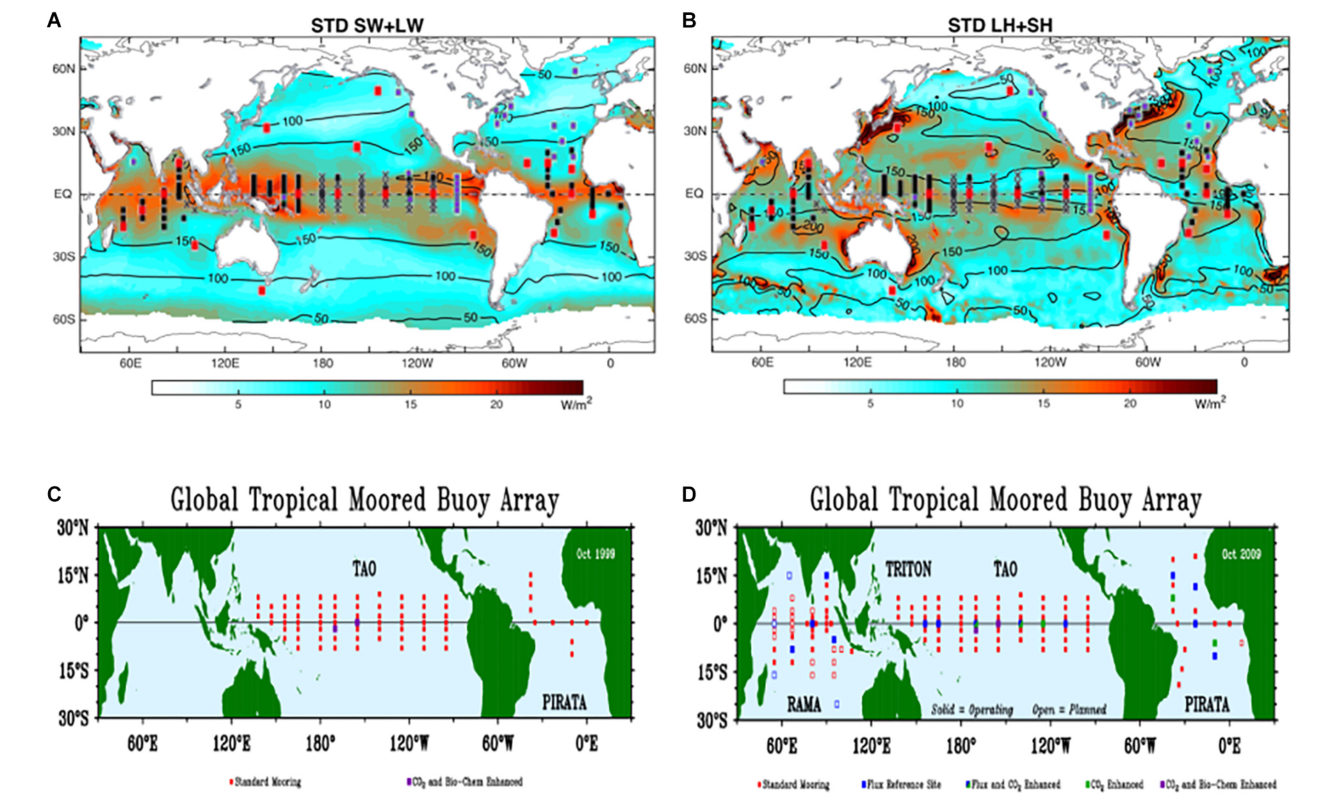

FIGURE 3 | Standard deviation of the means based on 14 products for **(A)** SW + LW and **(B)** LH + SH for the 10-year period of 2001–2010. Black contours denote the ensemble mean patterns. The location of the global moored surface buoys is superimposed, with red dots indicating flux reference moorings (adapted from Yu, 2019). Detailed instrumentation of the Tropical moored buoy array in panel **(C)** 1990 and **(D)** 2009 (from McPhaden et al., 2010).

datasets for improving the fidelity and consistency of ODA products in the subsurface ocean (Dombrowsky et al., 2009; Lee et al., 2009; Fujii et al., 2015)[2]. IndOOS is also an integral element of GOOS, which contributes observations to the Ocean Reanalysis Intercomparison Project (ORA-IP) (Balmaseda et al., 2015) which carries out intercomparisons and evaluations of a suite of ODA systems.

However, significant deficiencies in, and discrepancies among, ODA products remain. These arise from limitations both in forward ocean models and in data assimilation. In order to test the fidelity of ODA products at decadal and longer time scales, and to test the success of ODA for initializing seasonal-to-interannual prediction, the observational records need to be far longer to cover many more realizations of interannual and decadal events. Although some of the requirements of the initial phase of IndOOS have been adjusted as our knowledge, technologies and logistical challenges have changed, sustaining and enhancing IndOOS is an imperative. For example, the role of the deep ocean below 2000 m (the maximum profiling depth of the current Argo array) will become more important at longer time scales and deep-ocean structure in ODA products remains poorly constrained. It is therefore necessary to develop deep Argo observations under IndOOS.

[2]https://www.godae-oceanview.org/science/ocean-forecasting-systems

Other areas where IndOOS needs to be enhanced include coastal regions that are not sampled by Argo and RAMA, and the ITF which has profound effects on marine biogeochemistry and ocean-atmosphere coupling in the eastern and tropical Indian Ocean. A comprehensive strategy is needed to ensure the monitoring of the ITF.

The continuity and enhancement of satellite measurements can help alleviate the sparsity of *in situ* measurements in coastal oceans and elsewhere. The Indian Ocean has some of the most dynamic salinity signals, due in part to the influence of monsoon, river runoff, and the ITF (Godhe et al., 2015), therefore, the continuity and improvement of satellite salinity measurements is necessary. Wind stress measurements are critical to studies of Indian Ocean dynamics and ocean-atmosphere coupling. Of particular importance is the need to enhance the temporal sampling of satellite-derived wind and wind stress measurements – in the equatorial Indian Ocean and the region near the Maritime Continent strong diurnal variability in the winds is important to MJO and MISO development. Currently, there are only two continuity series of satellite scatterometers: the MetOp series by the European Space Agency (ESA) and EUMETSAT, and the Oceansat series by the Indian Space Research Organization (ISRO). These two scatterometers provide approximately 60% coverage of the ocean at the 6-h interval, the de-correlation time scale of the diurnal cycle. Wind measurements from additional scatterometers and passive microwave radiometers are needed to reduce the aliasing of diurnal variations into lower frequencies.

Observations for the Ocean Modeling Community

Simulations and numerical experiments with various levels of model complexity are useful tools for studying ocean circulation and its variability. Open source models, such as the Modular Ocean Model (Griffies, 2012), Hybrid Coordinate Ocean Model (Bleck, 2002), MIT General Circulation Model (Marshall et al., 1997), and Regional Ocean Modeling System (Shchepetkin and McWilliams, 2005), enable many scientists, even those with limited access to scientific resources, to run experimental, regional simulations. In addition, global high-resolution prognostic and data-assimilated simulations provide large amounts of four-dimensional data, some of which are shared among the science community for detailed analyses of the ocean from a variety of viewpoints (e.g., Masumoto, 2010; Forget et al., 2015). The IndOOS plays a key role in these ocean modeling activities by providing initial and boundary conditions as well as data for validation of output, hence the need for them to be continuously obtained with reasonable time and space resolution for a long period with good quality and accuracy, with requirements for resolution and data quality dependent on target phenomena.

IndOOS is a major data source for basin-scale variability in the Indian Ocean. Essential observations include large-scale density distributions and associated circulations derived from temperature and salinity profiles obtained by hydrographic observations and Argo floats among others, surface heat and momentum fluxes between atmosphere and ocean measured mainly by RAMA, and sea level data from tide gauges. Variables at the sea surface can be measured by satellite remote sensing, which provides high temporal and spatial resolution data, particularly for SST, sea surface salinity, surface height, and fundamental variables related to the surface heat and momentum fluxes.

Attempts to incorporate biogeochemical and ecological processes in numerical ocean and earth system models are ongoing (Hood et al., 2003; Wiggert et al., 2006; Dilmahamod et al., 2015) and the extension of IndOOS to observe biogeochemical properties (Strutton et al., 2015) will be key to the evaluation and success of these models. The simulations so far are limited due to the sparseness of biogeochemical observations compared to the diverse and multi-scale processes involved in biological and ecological dynamics.

Various indices that represent observed phenomena and conditions have been used for testing the ability of models to simulate realistic variability. Some examples are the ITF transport, as an inflow condition for Indian Ocean basin models (e.g., Meyers et al., 1995), the Dipole Mode Index (DMI) for interannual climate variations in the tropical region (e.g., Saji et al., 1999), and eddy kinetic energy distribution for validation of mesoscale fields in models (e.g., Chelton et al., 2011). These indices are needed over long durations, with temporal resolutions of 1 month or less, to investigate variability at interannual-to-decadal scales as well as interannual modulation of shorter time-scale phenomena such as MJO.

Needs From Forecasting and Prediction Community

The ultimate goal of both the observing and modeling communities is to provide accurate marine and weather forecasts and climate predictions. For this, sustained surface and subsurface information from RAMA, Argo, and other observing platforms of IndOOS are essential. For improvements in the prediction of weather and climate over the Indian Ocean rim countries and islands, and globally, we need to pay particular regard to the IOD, MISO, and the MJO. In parallel to this is the need to have a better understanding of the sub-mesoscale processes, particularly within the coastal regions and it is important to highlight the need for regional and process studies, in particular within countries EEZs for improved high resolution models. Ongoing issues around this is the availability of data and the need for the global modeling community to continue to work with countries, identifying the importance of such models for improved products which will benefit the countries.

Indian Ocean Dipole

Several studies have reported that the IOD could be predicted one season ahead with reasonable accuracy using a dynamical prediction system based on a Coupled General Circulation Model (CGCM) (e.g., Wajsowicz, 2005; Luo et al., 2008; Zhao and Hendon, 2009; Zhu et al., 2015; Liu et al., 2017). Some strong IOD events were actually predicted a few seasons ahead (Luo et al., 2008). Based on these scientific outcomes, a real-time forecast of the IOD is now provided every month by several institutions around the world [e.g., Japan Agency for Marine-Earth Science and Technology (JAMSTEC), BoM, United Kingdom Meteorological Office, Asia-Pacific Economic Cooperation Climate Centre].

However, many of the state-of-the-art CGCMs, such as the National Center for Environmental Prediction Climate Forecast System version 2 (CFSv2), still lack the skill to be significantly better than persistence in predicting IOD events (Zhu et al., 2015). The skill of IOD predictions is affected by event-to-event diversity that may be rooted in differing development mechanisms (Tanizaki et al., 2017). Moreover, some IOD events appear to be triggered by weather noise and intra-seasonal disturbances and have low potential predictability, while other events that co-occur with ENSO are more predictable (Song et al., 2008; Yang et al., 2015).

In an attempt to understand the role of subsurface conditions on IOD predictability, Doi et al. (2017) conducted two reforecast experiments based on a fully coupled GCM. One used only SST for the initialization, the other used SST plus subsurface temperature and salinity aggregated from *in situ* observations, such as XBTs, moored buoys, and Argo floats. Although the ENSO prediction skill did not change significantly between the two experiments, the IOD prediction skill was significantly improved. Feng et al. (2016) also showed that subsurface ocean observations can reduce large uncertainty in the IOD prediction, and may allow long-lead time prediction from boreal winter. Multi-decadal variability in the background state of the Indian Ocean also likely plays a role for IOD frequency, strength of the co-variability with ENSO, and predictability (c.f., Annamalai et al., 2005; Ummenhofer et al., 2017), as shown explicitly also for ENSO predictability (e.g., Jeong et al., 2015; Zhao et al., 2016). Continuation and expansion of surface and subsurface ocean observing platforms are necessary for continuing progress on prediction research and quasi-real time forecast services.

Madden–Julian Oscillation

The unique character of intraseasonal variability, and especially the MJO, in the Indian Ocean has become apparent through studies based largely on satellite SST microwave imagery and *in situ* observations during programs such as the Cooperative Indian Ocean Experiment on Intraseasonal Variability (CINDY)-Dynamics of the MJO (DYNAMO) in the central equatorial Indian Ocean (DeMott et al., 2015). The MJO is also a centerpiece in the emerging effort to develop skilled forecasts at subseasonal to seasonal (S2S) time scales (Vitart and Robertson, 2018). The MJO induces strong variability in SST along the western Indian Ocean thermocline ridge (Harrison and Vecchi, 2001; Saji et al., 2006; Vialard et al., 2008) and this variability feeds back onto the MJO (DeMott et al., 2015). With improved availability of SST from satellite, the signature of the MJO to the north west of Australia is now recognized to be larger than in the central Indian Ocean (Duvel and Vialard, 2007; Vialard et al., 2013). The amplitude of the diurnal cycle of SST is also strongly modulated by the MJO in this region (Bellenger and Duvel, 2009) and affects the mean SST and the intraseasonal SST variability (e.g., Shinoda and Hendon, 1998; Shinoda, 2005; Bernie et al., 2005). The modulation of the diurnal cycle of SST in the equatorial Indian Ocean can also help promote the onset of the convective phase of the MJO, through rectified effects on latent heat flux (Seo et al., 2014).

Observing and understanding the intraseasonal variation of the upper Indian Ocean driven by the MJO challenge the observing system because it requires high vertical resolution in the upper ocean, measurement of the diurnal cycle, and accurate measurement of surface fluxes. Duvel and Vialard (2007) propose that the maximum amplitude of intraseasonal SST variation occurs to the northwest of Australia because of peak MJO-driven variability of intraseasonal surface heat flux coincident with a shallow mixed layer. However, there are no direct measurements of the surface fluxes or the diurnal cycle of SST in this region of the Indian Ocean. This dearth of observations is reflected in differences as large as the mean between surface heat flux estimates from different re-analyses.

In addition to the IOD and MJO, the monsoon and its intraseasonal and interannual variability also plays a dominant role for the climate of Indian Ocean rim countries. Similar to MJO, the MISO is also an ocean-atmospheric coupled intraseasonal variability, originating in the equatorial Indian Ocean and influencing the active and break phases of the Asian monsoon. Both short-term (MISO) and seasonal monsoon predictions depend on the ocean initial conditions. Hence, the IndOOS observation program may potentially contribute to the improvement of monsoon prediction.

End User Engagement: Data Accessibility and Transparency

As discussed in Section "Societal Needs for Observing Systems", there are a range of societal needs for Indian Ocean observation capability, which arise given the complex interactions between observed phenomena and environmental benefits and risks including those associated with marine ecosystems (e.g., concerning fisheries, tourism), extreme events (e.g., casualties, damages to infrastructures), monsoon rains (e.g., agricultural productivity) and climate regulation generally. The utility of IndOOS to decision-making around these benefits and risks depends on the identification of, and engagement with, end-users of the System, and on the practical accessibility and transparency of data in a wide range of decision-making processes operating on multiple scales. Current progress, issues and challenges related to end user identification and engagement for IndOOS are surveyed below.

IndOOS has been developed in the context of rapid intensification of anthropogenic interactions with the Indian Ocean, driven by coastal population growth, coastal and ocean-based economic development, and other factors (Obura, 2017). Analysis published in 2016 by the Organization for Economic Co-operation and Development (OECD) forecasts sustained global growth in ocean-based economic activity, coupled with structural change resulting from growth in "emerging sectors" such as aquaculture, offshore energy infrastructure, marine biotechnology, and maritime safety and surveillance (OECD, 2016). Many economic sectors in the Indian Ocean region are fundamentally underpinned by marine environmental goods and services (Obura, 2017). Analysis of the status of these depends on access to a wide range of social, economic and environmental data, including the outputs of IndOOS that focus as explained above on biogeochemical, oceanographic and atmospheric data.

A major challenge for economic decision-makers across the Indian Ocean region is the severe fragmentation of data – supplied by IndOOS and many other sources – relevant to integrated analysis of environmental dependencies and risks associated with economic activity. Macro-economic data in most Indian Ocean countries is largely standardized and collected regularly through national accounting processes, organized in terms of the UN System of National Accounts (United Nations et al., 2008). Since 2012 a growing number of countries have undertaken efforts to develop integrated accounting frameworks for environmental statistics that are compatible with the structure of SNA accounts, supported by the UN System for Environmental Economic Accounting (SEEA; United Nations, 2018a), Framework for Development of Environment Statistics (FDES; United Nations, 2018b), and related approaches. The application of these approaches to ocean observation data has been very limited to date. In 2018 the UN established an Ocean Accounts Partnership that is specifically designed to address this deficiency, through pilot application of FDES, SEEA, and the SNA to ocean-related data and statistics (ESCAP, 2018). This intergovernmental effort has important implications for IndOOS and ocean observation generally, because it offers opportunities for "value-addition" to fundamental ocean-observation data through integrated presentation and analysis alongside relevant social, economic and other environmental data.

Beyond the realm of economic decision-making, an important group of end-users for IndOOS data are those involved in the planning, monitoring and reporting of wider efforts to achieve sustainable development in the Indian Ocean region, in line with national priorities and international commitments such as the 17 sustainable development goals (SDGs) and 169 associated Targets (UNGA, 2015). These efforts are characterized by the central role of national and international indicators of sustainable development, which relate to a very broad range of subject matter including poverty alleviation, ecosystem condition and services, food security, risk and resilience, consumption and production, climate change, and other factors where IndOOS data may (or may not) be of relevance (U. N. Statistics Division, 2018). In this context a pressing technical challenge is the need to clearly identify the ocean observation data dependencies of these indicators, and practical methods for indicator compilation based on IndOOS and other data, which accommodate the acute capacity challenges in many Indian Ocean countries (see section "Key Regional and Process Efforts Connecting With IndOOS"). Considerable progress to these ends has already been achieved through efforts to define "Essential Ocean Variables" for sustained observation of biodiversity and ecosystem changes in light of societal needs as defined in the SDGs (Miloslavich et al., 2018).

The end-user community for IndOOS also includes scientific and technical experts in other disciplines, including ocean-focused ecologists, economists, geographers, policy analysts, and many others. For this group of end-users, engagement challenges include the need to connect specialized use-cases for ocean observation data (i.e., ocean state estimation, atmospheric re-analyses, and surface flux estimation) with other fields of analysis (e.g., ecological assessment, input-output analysis, cost-benefit analysis). This also serves to highlight the need for the links with regional and process orientated observing programs. Opportunities also exist to leverage the capability of global data analysis and communication initiatives for the benefit of ocean observation specifically tailored to meeting societal needs in the Indian Ocean region. For example institutional and data connections with the Blue Planet Initiative of the Group on Earth Observations (BP-GEO) could leverage BP-GEO's aims to address global challenges and improve decision-making through coordination and development of Earth observation efforts among 105 Member governments, supported by several non-governmental organizations (GEO, 2017).

There is a strong need to ensure that Indian Ocean rim countries have access to the data produced through IndOOS, as well as understanding its applications. As highlighted in Section "Capacity Development", a number of workshops have taken place in order to implement this, but these efforts need to be sustained. A possible mechanism for continuing this and for ensuring that IndOOS reaches Government stakeholders and policy makers is to use the Indian Ocean Rim Association[3] and its sub grouping of the Academic Group. IORA is an intergovernmental group (22 member states and 9 dialogue partners) set up to support socio-economic activities between these countries. A large subset of the Indian Ocean rim countries are also members of the Commonwealth (of Nations), which is providing a forum for the integration of ocean observations in delivering against SDG targets and United Nations Framework Convention on Climate Change (UNFCCC) requirements through its Commonwealth Blue Charter action group on the topic.

FUTURE VISION

IndOOS Enhancement

The main focus of IndOOS is to maintain a sustained basin-scale observing system, which is flexible in terms of emerging technologies and issues (such as marine heat waves in response to a changing climate and plastic pollution) and provides a framework for enhanced regional and coastal monitoring. Looking forward, the IndOOS needs to be sustained, modified, and enhanced to meet societal need for improved understanding and predictability of Indian Ocean climate (**Figure 2b**).

The recommendations of the IndOOS decadal review, which will be finalized in 2019, are given in tiers. Tier I relates to sustainment of the *essential* components of IndOOS, while streamlining the observing system in consideration of redundancy and logistical constraints: Core *in situ* programs with upgraded technology, satellite observations, and ITF monitoring; Tier II lists *priority* enhancements to extend IndOOS capacities to better address scientific and operational drivers: Including increasing biogeochemical measurements, boundary flux arrays and increased engagement with Indian Ocean rim countries and Tier III lists *desirable* components: Pilot projects that promote advancements, some of which may be integrated into the IndOOS and contribute to its sustainability, as well as enhancements with new autonomous and expendable platforms and new sensor technologies.

Expanding the Current Observations

With the reduction in piracy, the expansion of the RAMA array westward must be completed to capture air–sea interaction important to intraseasonal and monsoon dynamics, as well as cross-equatorial heat transport and processes underpinning the strong oceanic productivity and variability of the marked OMZ in this region. The RAMA array also requires enhancement in the vertical resolution of temperature and salinity measurements, and direct flux measurements at key sites in order for improved subseasonal-to-seasonal forecasting and surface flux products. Argo floats need to be doubled close to the equator (10°S to 10°N) to improve the resolution of intraseasonal to interannual variability which is critical for observing and predicting IOD, monsoons, and MJO. Increasing the number of Argo floats with biogeochemical sensors, particularly in

[3] http://www.iora.int/en

regions of upwelling and OMZ such as the Arabian Sea and Bay of Bengal, is a priority in order to capture the links between physical climate and ecosystem changes. The BGC-Argo implementation plan is for 1000 floats globally, based on several OSSE, translating to 200 biogeochemical floats in the Indian Ocean, which represents 20% of the global ocean. Core biogeochemical sensor specification includes dissolved oxygen, nitrate, pH, chlorophyll fluorescence, optical backscattering and downwelling irradiance (Johnson and Claustre, 2016). Presently there are 105 floats with biogeochemical sensors, although none yet conform to this full design specification. Given that it is prohibitively expensive to deploy enough sensors at the most useful depths on moorings alone and that there are no moorings in some of the most biogeochemically important regions, such as the Western Arabian Sea and the Madagascar bloom, BGC sensors on Argo floats will be a vital part of the future of IndOOS. Although the number of presently active Argo floats overall is a positive sign, the funding levels of many nations are either flat or declining, posing a serious challenge to enhancing and sustaining the array (Durack et al., 2016). This is compounded considering that biogeochemical Argos are three-to-four times as expensive compared to Argos, in terms of equipment, maintenance and human resources (Johnson and Claustre, 2016).

In addition, Deep Argo needs to be piloted and expanded, given that the deep ocean below 2000 m, especially in the Southern Hemisphere mid-to-high latitudes, contributes a significant fraction of the total water column increase in heat content and thermosteric sea-level rise (Fukasawa et al., 2004; Johnson et al., 2008; Purkey and Johnson, 2010, 2013). Based on the global design goal of one deep Argo float per 5° × 5°, the Indian Ocean requires at least 250 floats north of 40°S, while currently there are 14 (**Figure 2c**).

Surface drifters need to be augmented with barometric sensors to support weather and seasonal forecasting. Essential XBT lines such as those monitoring the ITF output or crossing the Arabian Sea upwellings need to be maintained or enhanced, as do western and eastern boundary arrays in the southern subtropical gyre, to quantify mass and heat fluxes and improve predictability of basin-scale heat content change. The Global Sea Level Observing System (GLOSS) network needs to be expanded and data made available. Utilization of new autonomous and/or expendable platforms and new sensor technologies should always be explored for enhancements of IndOOS.

It is not just *in situ* observations that need to be enhanced; satellite missions provide key variables to complement IndOOS and need to be supported to ensure good continuity for EOVS, in particular measurements of surface winds at diurnal timescale, all-weather sea surface temperature, sea surface height, sea surface salinity and ocean color are of highest priority (Essential Tier I). *In situ* data provides calibration, validation and extrapolation (e.g., from surface to vertical) of satellite measurements and help de-alias signals that are not adequately sampled.

The focus of the aforementioned observations are beyond the EEZ, however, future observing systems need to consider the coastal zone, as a key region for understanding and monitoring the ocean's influence on, and response to, climate change processes. Coastal dynamics play a substantial role on the open ocean by modulating air–sea fluxes and distributing nutrients and marine plankton, and influencing the monsoon variability and MJO (e.g., Prasanna Kumar et al., 2001; Vialard et al., 2012). While the coastal zone is not directly covered by IndOOS currently, except for the expansion related to boundary current arrays, future enhancement of IndOOS needs to include these waters (Tier III; pilot projects, exploring IndOOS integration) for the study of coastal currents, coastal heatwaves OMZ, ocean acidification, carbon uptake, land sea interaction through, for example, effluent discharge from terrestrial sources and other critical processes, which infringe on or occur within EEZs and which are especially poorly monitored in the Indian Ocean. Future work also needs to consider the complex relationships between society and the sea, in particular around the impacts of human exploitation on marine resources and the impacts this has. The coastal regions of the Indian Ocean rim countries are the most densely populated of any region and vulnerable to changing sea levels, warming ocean temperatures, deteriorating marine ecosystems and extreme weather events (Nicholls and Cazenave, 2010). Societal needs and scientific benefits are greatest within the coastal ocean, and hence it is essential to monitor these regions. Autonomous devices such as gliders have great potential to measure the coastal ocean. It is imperative that coastal states allow open access to monitor physical and biogeochemical parameters in these regions. A first step in this direction has been achieved through the Argo float program and there is an ongoing process being led by the World Meteorological Organization (WMO) and Intergovernmental Oceanographic Commission (IOC) to come to an agreement around observations in EEZs,[4] but it remains a complex, legal task. Where possible the IndOOS community needs to support national efforts of Indian Ocean rim countries, including through capacity building, in setting up long-term observing programs and ensuring that measurements are relevant and quality-controlled and that the data is archived and shared.

Key Regional and Process Efforts Connecting With IndOOS

Although IndOOS does not have a specific focus on regional and process-orientated observing programs there are important synergies. IndOOS provides a framework to facilitate, support, and enhance them, while regional programs may also support IndOOS, for example, through ship time and deployment of assets. To this effect, six key examples or regional and process efforts, which should be sustained, in conjunction with IndOOS are:

(a) Changes in OMZs and impact on ecosystem, fish distribution and decline.

In a region where many people are dependent on fisheries for their livelihoods (Barange et al., 2014) the motivation for improved understanding and forecasting of OMZs is

[4]https://public.wmo.int/en/events/meetings/technical-workshop-enhancing-ocean-observations-and-research-and-free-exchange-of

evident, particularly in the intense marine productivity region of the North Indian Ocean. As a whole, Indian Ocean biophysical processes and the carbon cycle remain poorly understood. To address this, the RAMA array will be extended into the western Indian Ocean/Arabian Sea and Bay of Bengal with biogeochemical sensors, Biogeochemical (BGC)-Argo deployments will be prioritized in a number of key areas, and a portion of the IX01 XBT line will be re-activated.

(b) Integrated physical, chemical, and biological observations south of Java and Sumatra upwelling systems.

Recognizing the importance of the upwelling systems in the Eastern Indian Ocean, integrated physical, chemical, and biological observations south of Java and Sumatra are being rolled out as part of the Second International Indian Ocean Expedition (IIOE2, Hood et al., 2015). Biogeochemical cycles, such as carbon and nitrogen cycles, and ecosystems in this region respond to the background physical conditions, as observed by RAMA and other IndOOS assets, showing significant responses to variability at various time-scales spanning hours to long-term trends. The ecosystem is also influenced directly by human activities such as nutrients in river discharge, increasing aeolian dust flux, ocean acidification, overfishing, and increasing pollutants (e.g., Jickells et al., 2017). Understanding possible mechanisms of physical, biogeochemical, and ecosystem responses to natural and anthropogenic perturbations is an emergent issue of marine science, with increasing human activity degrading the quality and quantity of marine ecosystem services on which our society is dependent. The main part of this activity consists of *in situ* observations using research vessels. Data from IndOOS will be utilized as background information to this research activity and, in turn, RAMA sites will be maintained and new technologies tested for IndOOS.

(c) Surface fluxes and diurnal mixed layer variability at key tropical sites and improvement of monsoon, MJO, and MISO prediction.

Increasing societal demand for seasonal to decadal climate predictability in the face of global warming makes the need for strategic, sustained observations in the Indian Ocean more urgent. In particular, a Tier II recommendation of the IndOOS decadal review states the need for air–sea flux reference sites in key tropical areas to collect measurements of high temporal resolution, including upper ocean properties, to complement satellite observations. A regional program supporting this effort is the Timor Sea Flux Station (TSFS), aimed at observing diurnal to seasonal variability in surface fluxes, mixed layer ocean structure, and surface meteorology. The location of the TSFS has been chosen to target the MJO and its interaction with the ocean and the formation of diurnal warm layers (**Figure 2b**, purple square). Better understanding of the MJO is a high priority for the Australian Bureau of Meteorology (BoM) as it impacts on rainfall forecasts across much of Australia. SST (and heat content) at the location of the proposed mooring exhibits strong correlations with seasonal rainfall over mainland Australia, which may be independent of large-scale ocean dynamics, such as IOD, at times.

(d) Monsoons and associated air–sea interactions.

The monsoons impact large populations and understanding and prediction of monsoon dynamics needs improvement over the next decade. Since March 2010, the South China Sea Institute of Oceanology (SCSIO), Chinese Academy of Sciences has established a hydrological and marine meteorological observation network over the tropical eastern Indian Ocean to enhance the understanding of monsoonal air–sea interaction. This includes 9 years of Indian Ocean cruises collecting continuous oceanic and meteorological observations, including conductivity, temperature, and depth (CTD) measurements, Global Positioning System radiosonde, and automatic weather station data (**Figure 4**). Observations prior to the monsoon are very important because the air–sea interaction within these periods can be a precursor for monsoon onset. Data from these *in situ* observations will have an important value for assimilation into ocean re-analyses and for weather and seasonal forecast models.

(e) The Agulhas Current System and associated air–sea interaction and upwelling.

Measuring the Agulhas Current has been identified as a Tier II future priority in the IndOOS decadal review, largely owing to its dominant role in basin-wide heat and freshwater budgets. For western Indian Ocean countries, particularly South Africa, measurements of the greater Agulhas system and its leakage are also a priority, given its influence on regional climate and ecosystems, yet there is no integrated observing system for the region. Since 2010, the US led Agulhas Current Timeseries (Beal et al., 2015) was followed by the South African and US led Agulhas System Climate Array (ASCA; Morris et al., 2017), however, ships' availability and lack of resources resulted in the early termination of ASCA in 2018.

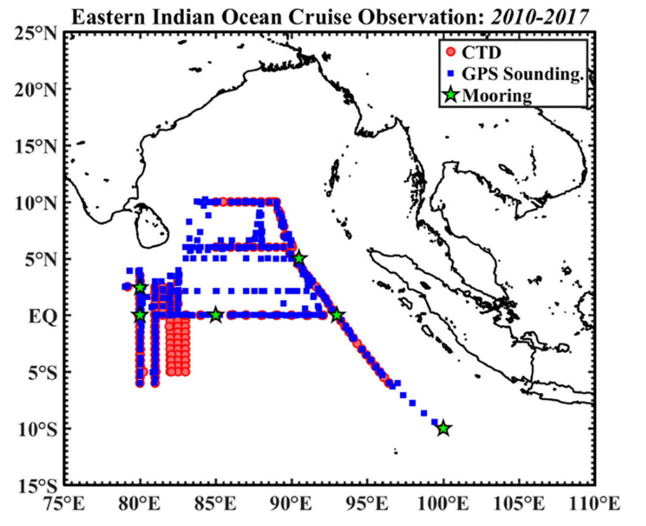

FIGURE 4 | Observation stations of the Eastern Indian Ocean cruises led by the South China Sea Institute of Oceanology, Chinese Academy of Sciences during 2010–2017.

Observations and satellite remote sensing have highlighted significant limitations of ocean models of the region. These model errors directly affect the ability to routinely predict the marine and maritime environment, adversely affecting management and policy decisions and stunting the growth of the ocean economy in southern Africa. Furthermore meso- and submesoscale processes, which directly influence rainfall, are central drivers of oceanic connectivity and productivity around southern Africa, where food security is of utmost importance. The inability of coarse resolution climate models to accurately resolve these processes lead to uncertainties of future climate projections. The South African community is working to design and implement a cost-effective and regionally appropriate integrated ocean observing system, tailored to provide routine monitoring of key parameters, strengthen the understanding of crucial processes, and help accelerate model development. Key elements are an Agulhas array enhanced with glider measurements over the shelf and slope and a full depth mooring array into the southeast Atlantic and other dedicated, multi-disciplinary programs (Morris et al., 2017; Paterson et al., 2018). This will better enable end users to manage marine ecosystem health, pollution, hazards and maritime safety and help to build a society resilient to climate variability and change.

(f) Cross-equatorial overturning cell.

In the eastern equatorial Indian Ocean six deep moorings, extending down to 1000 m with upward- and downward-looking Accoustic Doppler Current Profilers (ADCPs) have been occupied by SCSIO since 2015. This array follows the deep ocean current meter moorings maintained by India last decade and will measure variations associated with the cross-equatorial overturning cell in the Indian Ocean. The dynamic processes of the equatorial deep Indian Ocean influence the mass and heat budgets of deep ocean variability (Chen et al., 2016; Huang et al., 2018a,b,c).

Measuring the variability of these regional components contemporaneously is a future vision of IndOOS and will improve the understanding and predictability of Indian Ocean climate. For example, the heat and freshwater budgets of the Indian Ocean are dominated by three components of similar magnitude (**Figure 2c**): an inflow of fresh tropical waters via the ITF (Sprintall et al., 2009; Roberts et al., 2017; Zhang et al., 2018); an upper-ocean overturning cell linking upwelling in the Northern Hemisphere and in the Seychelles-Chagos thermocline ridge with subduction of mode waters at the southern reaches of the basin (Schott et al., 2009; Han et al., 2014); and a horizontal gyre circulation dominated by the warm and salty waters of the Agulhas Current (Bryden and Beal, 2001). The ITF is thought to be shoaling and strengthening as a result of strengthening Pacific Trade winds and increasing rainfall over the Indonesian Seas (Wijffels et al., 2008; Feng et al., 2011; Sprintall and Révelard, 2014; Hu and Sprintall, 2017) and has been put forward as the main proponent of rapid Indian Ocean heat gain (Lee et al., 2015; Zhang et al., 2018). However, warming is a maximum at the southern reaches of the basin, far from the ITF, and within the Agulhas system (Alory et al., 2007; Wu et al., 2012), where variability in the other components of the heat budget are more poorly constrained. There are decadal changes in Indian Ocean thermocline waters, which reversed from freshening (Bindoff and McDougall, 2000) to becoming saltier (McDonagh et al., 2005), while the subtropical gyre may be spinning up and expanding in response to strengthening Westerlies (Palmer et al., 2004; McDonagh et al., 2005; Alory et al., 2007). Yet an increase in southward heat transport appears related to warming, but not strengthening, in both the Agulhas and Leeuwin Currents (Beal and Elipot, 2016; Hernández-Guerra and Talley, 2016; Zhang et al., 2018).

The Importance of Linking IndOOS to Regional Efforts

It is essential that the international community support the regional efforts, as they are generally considered more relevant by the various Indian Ocean rim governments due to the direct impact on the coastlines. The regional programs are also very valuable for the re-analyses community. As prioritized through IndOOS, dense, daily-to-monthly observations of velocity, temperature, and salinity across the ITF, Agulhas, and Leeuwin Currents, are needed, combined with hydrographic end-point moorings, similar to those used to measure the Atlantic overturning (Johns et al., 2011), across the open southern boundary of the basin. Continuation of existent Argo, satellite (sea surface height, wind), and GO-SHIP programs are also essential. However, monitoring boundary currents and exchanges like the ITF and Agulhas Current is a particularly challenging frontier due to their dynamic environments and small time and length-scales. Innovative strategies for integrated observing systems are required, for example combining current meter arrays, gliders, and Current and Pressure Inverted Echosounders with periodic hydrographic sections for important climate variables such as carbon, nutrients, and oxygen. In addition, innovation in real-time data return for subsurface arrays, such as fast telemetry and data pods, is necessary.

Future strategies for IndOOS, particularly regarding connection to end users and stakeholders, need to be better linked to regional and national efforts, such as via the GOOS Regional Alliances. A key factor affecting investment in scientific research is the level of national appreciation of the importance of the marine sector to the country's economy and resources. GOOS (and associated Regional Alliances) is in a unique position to be able to make the case to national governments and stakeholders (GOOS strategy) through the IOC of the United Nations Educational, Scientific and Cultural Organization (UNESCO). To support regional capacity development and involvement in the sustained observations, international partnerships need to be fostered and maintained, in particular with Indian Ocean rim countries. Intergovernmental bodies such as WMO and IOC, as well as international scientific bodies such as CLIVAR and Scientific Commission for Oceanographic Research (SCOR) can be used to help facilitate this. It is essential to improve evaluation mechanisms for what has been achieved to date and consider long term thinking around funding mechanisms. These programs also serve a vital role with regards to performing observations and accessing data held within countries EEZs.

IMPLEMENTATION CHALLENGES FOR IndOOS

Sustained observing systems over the Indian Ocean face general challenges as is common to all basin-wide observing systems. However, the Indian Ocean has its own unique challenges due to the physics of the basin, as described, as well as the problems within the Indian Ocean countries that rely heavily on coastal regions for food security. Special focus needs to be placed on access to EEZs for observing system components (such as boundary arrays), and on capacity, resource and coordination development of rim countries that remains a challenge due to human resources, finances, and logistics. International coordination, best practices, and data sharing are also challenges. With strong potential synergies between IndOOS, process studies, and regional observing systems (see section "Key Regional and Process Efforts Connecting With IndOOS") integration and mutual interactions have not developed satisfactorily over the last decade. There is a need to develop an effective strategy for merging regional and process oriented observing systems with the basin-scale IndOOS.

Access to the EEZ

The coastal zone is especially poorly monitored in the Indian Ocean, yet societal needs and scientific benefits are most immediate within the coastal ocean and hence it is essential to systematically observe these regions. Some regional observing systems have been developed and work well within the GOOS Regional Alliance system, for example the Integrated Marine Observing System (IMOS) of Australia. In general, marine observations for research purposes are permitted with appropriate applications to countries, whose EEZs and/or territorial waters include observation fields. However, some countries are apprehensive about deploying, permitting, or making freely available ocean measurements in their EEZs for concerns over national security, resource development, or other reasons. Research cruises undertaken on foreign ships are often not allowed to measure in EEZs and must cease sampling when they transit through an EEZ. Some countries restrict access to coastal tide gauge station data, either in real time or delayed mode. In June 2018 the Secretary of the Indian Ministry of Earth Sciences (MoES) announced that its OMNI data would be made freely available outside the Indian EEZ, while data availability is still restricted for OMNI moorings inside the EEZ. When Argo and bio-Argo floats deployed in the open ocean drift into an EEZ, the deploying nation must inform the respective coastal state (IOC Resolution EC-XLI.4) via the Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM) *in situ* Observing Programs Support Centre (JCOMMOPS) (though no country has asked that Argo data be turned off within an EEZ).

The problem of measuring in EEZs is a longstanding one that complicates both the implementation of IndOOS and utilization of its data. However, this reality does not diminish the imperative to systematically observe in EEZs, as these regions are crucial from both a scientific and a societal perspective. The IndOOS community can be an effective agent for change by highlighting these needs and the benefits that a more open access policy can deliver.

Capacity Development

Capacity development is essential for training the next generation of researchers and technicians and for ensuring that Indian Ocean rim countries take ownership and contribute toward the sustainability of observing systems, as well as the use and dissemination of their data. The transfer of knowledge and information through capacity development is not only an essential pursuit in its own right, for the direct applied benefits that it brings to society, but also important in raising awareness of the benefits of ocean observations to decision and policy makers and their constituents, thereby enhancing the case to support and resource the essential components of IndOOS.

From the initial planning in the late 1990s and the subsequent implementation of the IndOOS, through to the more recent efforts of the related, multi-national program of IIOE-2, capacity development has been woven in as a critical element to demonstrate the utility of Indian Ocean data. To date approximately twenty capacity development workshops have been held across the Indian Ocean basin under the auspices of IndOOS to ensure broad understanding in the rim nations of the social and economic applications and benefits of IndOOS, as well as technological training in sustainment of these vital meteorological and oceanic observations. Some examples of established capacity development programs include the Partnerships for New GEOSS (Global Earth Observing System of Systems) Applications (PANGEA[5]). PANGEA provides in-country practical training in applications of ocean data to large and diverse groups of regional participants, fostering partnerships between developed and developing countries to realize the social-economic benefits of ocean observing systems. As part of their contribution to the PANGEA concept a series of six Western Indian Ocean capacity development workshops have been convened by JCOMM's Data Buoy Cooperation Panel (DBCP) Task Team for Capacity Building (TT-CB), with the overarching goal to empower developing States by providing expert training on the applications of ocean observation data for understanding and predicting regional weather, ocean, and climate and their impact on fisheries, coastal zone management, natural disasters, water resource management, human health and others.

In addition to individual capacity development workshops, several JCOMM PANGEA "Resource-Sharing" long-term Partnerships have been fostered to implement and sustain the IndOOS and deliver training in practical application. These include formal partnerships between the U.S. National Oceanic and Atmospheric Administration (NOAA) and India's MoES and between NOAA and the Indonesian Agency for Meteorology, Climatology and Geophysics (BMKG). NOAA's in-country annual capacity development workshops

[5] www.jcomm.info/pangea-concept

in Indonesia have demonstrated practical applications of ocean observations through training by scientists from NOAA's Pacific Marine Environmental Laboratory (PMEL), Climate Prediction Center (CPC), and Ocean Prediction Center (OPC). BMKG has recently made the decision to invest USD $150M in the Indonesian Seas for maritime observations to advance societal-economic applications in S2S climate forecasting, shipping, fisheries, and other applications. Indonesia's major investment will contribute to observing capacity in the eastern Indian Ocean.

In parallel with these efforts, a major capacity development initiative strongly aligned with IndOOS is that coordinated through the IIOE-2. For example, all IIOE-2 endorsed projects are required to include capacity development elements into their frameworks, such as berths on research vessels and opportunities for fundamental science projects for young and emerging scientists and practitioners. The IIOE-2 also has capacity development built into its overall framework through the IIOE-2 Early Career Scientists Network, which at present has more than 500 members. The IOC institutional capacity development programs also connect with IndOOS and its science community through specific training programs, and through data and information management initiatives coordinated out if the IOC's Oostende regional office and associated with the International Ocean Data Exchange (IODE) program (including the OceanTeacher Global Academy).

Thus far, basin scale observations receive only small amounts of funding from developing countries. However, support for programs within EEZs is essential and hence such programs should ideally involve rim countries from inception. The GOOS Regional Alliances (e.g., Indian Ocean GOOS (IOGOOS), IMOS, The Southeast Asian GOOS, GOOS-AFRICA) provide connections among government institutions for support of such regional programs and the IOC framework can provide an understanding of the needs of a country. IOC Regional Subsidiary Bodies and Regional Committees play a similar role through their own capacity development programs [e.g., IOC Sub-Commission for Africa and the Adjacent Island States (IOC AFRICA), IOC Sub-Commission for the Western Pacific (WESTPAC), IOC Regional Committee for the Central Indian Ocean (IOCINDIO)]. Similarly, national efforts through regional training centers (e.g., the Regional Training and Research Center in China and Indonesia) and IOC Category II Centers for training and education (e.g., in the Islamic Republic of Iran and India) provide expertise and logistical resources for capacity development programs, which can and do take advantage of valuable IndOOS data. Many countries in the Indian Ocean rim do not have extensive marine organizations, or they are relatively small sections within government departments such as fisheries or meteorological services, and these sections need to be enhanced and developed. With evolving new autonomous technologies the scope to increase capacity development both in the technical and science realms is growing. It is important to share experiences and efforts in a coordinated manner and to continue to ensure societal relevance of the science and predictive capacities that comes from IndOOS.

International Coordination

IndOOS comprises satellite and *in situ* measurement systems operated by a wide variety of institutions in many different countries. As such, it is a major effort to coordinate implementation and maintenance of the network and maximize its societal benefit. To give one example of the scope and complexity of the undertaking, RAMA partners have conducted 85 cruises on 21 different ships from 11 different nations, using 2053 days of ship time to deploy and recover 325 moorings in the 14 years since September 2004.

The *in situ* components of IndOOS were designed, implemented and, since 2004, scientifically guided by a group of scientists within the IORP established under the World Climate Research Programme (WCRP)-CLIVAR and IOC-GOOS and aligned with IOGOOS. The IORP seeks to include and encourage all the rim countries to participate in the scientific leadership of IndOOS, and to contribute through not only observing platforms themselves but also technical transfer, capacity development, and data management and dissemination. Resources for the sustainment of the IndOOS, and for the recommended enhancements of the IndOOS moving forward, are a significant issue, particularly the human resources, shiptime, and equipment necessary for keeping the system healthy and quality-controlled data freely accessible. The IRF helps to find and coordinate national contributions to the observing system, while minimizing duplication of effort and maximizing scientific return on investment.

Beyond the IORP and IRF, each observing system element has its own global coordinating body. For satellites, there is the Committee on Earth Observation Satellites (CEOS); for moorings, the Global Tropical Moored Buoy Array (GTMBA) office at NOAA/PMEL and the Tropical Moored Buoy Implementation Panel (TIP); for drifting buoys, the GDP; for tide gauge stations, the GLOSS; for XBT and related observations, Ship of Opportunity Program; and for repeat hydrographic measurements, the GO-SHIP program. For Argo, the Argo Science Team provides overall scientific guidance. Indian Ocean Argo deployments are coordinated by Argo Regional Data Center[6] along with the Argo Information Center (AIC), including information on ships of opportunity and research vessels and guidance on regional float deployments.

JCOMM strives to integrate across these observing system programs to provide data management and services for the GOOS. The JCOMM Observations Program Support (OPS) Centre provides support services for the coordinated implementation of the observing system. Also within JCOMM is the DBCP, which focuses its efforts on coordinating the application of autonomous data buoy data. Within the DBCP are several Action Groups, one of which is the TIP whose goal is to coordinate across tropical moored buoy programs, such as RAMA. These nested and overlapping scientific, implementation, and resource bodies ensure a high degree of coordination

[6] http://www.argo.ucsd.edu/ARC.html

such that accumulated knowledge concerning measurement technologies and strategies is shared for the benefit of both data providers and users. However, there is limited representation at these international level committees of Indian Ocean rim countries and small island developing states.

Best Practices

One of the challenges for IndOOS is ensuring the quality and accuracy of data. Sustained measurements need careful calibration and inter-calibration if they are to provide records of climate variability and change. As described in the previous section, IndOOS has been implemented via a variety of national and international programs and projects, across which observing practices and data quality can be heterogeneous. At the regional level there are sometimes less capabilities for ocean observing. JCOMM programs such as GLOSS function well, with technical transfer and support offered and Indian Ocean rim countries taking ownership of high quality data due to the importance and direct impact sea level rise has on their coastal communities. The deeper ocean measurements (e.g., through Argo and GO-SHIP) are dominated by Australia and India in terms of rim countries and farther afield by the US, Europe and China. This is due to access to ship time and funding for equipment as well, in part, to the limited understanding of the relevance of deep ocean observations to developing nations.

For climate quality data there needs to be a clear understanding of the required levels of accuracy and an adoption of best practices, particularly in data collection and calibration, such as provided by the GO-SHIP manual (Hood et al., 2010). This level of accuracy is not always familiar to countries and may be beyond their means. However, if the observations are to be sustained as part of IndOOS then the data needs to be of climate quality so that they inter-calibrate across the years and decades Therefore, creating partnerships through intergovernmental systems and bilateral agreements and allowing for technical transfer onboard cruises is an essential way to develop capacity and promote best practices across Indian Ocean rim countries. It is important that this is an end-to-end approach with support at the pre-cruise planning, at sea training and calibration, as well as validation and data processing. Best Practice guides may need to be adapted to regional conditions of deployment and maintenance of observing networks (GOOS implementation plan). The IOC and GOOS regional alliances, along with IndOOS provide essential links to government organizations, as well as researchers, enabling them to get support with best practices, and access to opportunities for at-sea research.

Through an international working group on best practices, supported by the JCOMM Observations Coordination Group, IOC/IODE, GOOS, and the European Commission Horizon 20/20 AtlantOS a best practices repository[7] has been set up to allow community approved best practices to be easily accessible, combined with information about training courses, peer review publications, and digital object identifiers (Hermes et al., 2018) as well as various capacity building networks.

[7] oceanbestpractices.net

Data Sharing

IndOOS operates under the auspices of IOC-GOOS, IOGOOS, and CLIVAR. As such, the IndOOS data policy derives from and is fully compatible with those of the IOC, WMO, JCOMM, CLIVAR, and other programs of the WCRP. The policy is predicated on the principle of free, open, timely and unrestricted access to all data and associated meta data that is generated as part of the sustained observing system. IndOOS data are collected for a wide variety of uses, such as scientific research, weather and climate prediction, coastal zone management, fisheries regulation, navigation, search and rescue, and other applications beneficial to society. For many of these purposes real-time data delivery is a priority, and for some quality assurance through inter-calibration is a necessity. Quality control, product generation, and data archiving are part of the end to end IndOOS data system of collection, dissemination, utilization, and preservation.

IndOOS data are available from a wide variety of sources including World Data Centers like NOAA/National Centers for Environmental Information, Global Data Assembly Centers in Brest, France and Monterey, California, and project specific sites like for RAMA (PMEL, JAMSTEC, MoES), drifters (NOAA-Atlantic Oceanographic and Meteorological Laboratory), and sea level (University of Hawaii Sea Level Center and Permanent Service for Mean Sea Level in the United Kingdom).

Data from nation-specific coastal observing programs within EEZs are sometimes not as freely available (see section "Access to the EEZ"). Also, data from process-oriented studies are often technically specialized and may require an extended period of post-processing before they make it into appropriate archives. Not all nations involved in IndOOS, many of which border the Indian Ocean rim, are equally equipped to collect and process relevant data sets. So capacity development (see section "Capacity Development"), international coordination (see section "International Coordination") and sharing of best practices (see section "Best Practices") are needed to ensure that all countries willing to participate can contribute in meaningful ways to the overall IndOOS effort.

Summary of IndOOS Future Challenges

In summary, observing in EEZs remains a complex challenge, in particular for free drifting (e.g., Argo) and piloted (e.g., gliders) technologies. A recent effort led by the WMO (Technical Workshop on Enhancing ocean observations and research, and the free exchange of data, to foster services for the safety of life and property) brought together scientists, policy makers and lawyers to explore resolutions. In addition to this, capacity development is continually highlighted as a necessary and important factor in ocean observing. There are many different ways to improve capacity development, but it is key that all countries are involved in the discussions from the beginning and that the flow of knowledge is two ways. This can be enhanced through the international coordination efforts which look at the resources, as well as other partnerships. There needs to be improved discussions at governmental levels of all countries with an interest in observing the Indian Ocean and the community-driven recommendations from the IndOOS review should help guide these.

With constantly emerging new technologies and improving capabilities there is little doubt that the global observing systems in the ocean will look different 10 years from now (Legler et al., 2015) and any future vision needs to be flexible. Sensor developments will lead to a much greater range of variables being measured autonomously than are presently acquired. Voluntary observing ships with more automated equipment will enhance the system and feedback into the real-time observations necessary to provide data for assimilation into models for operational oceanography. The recently proclaimed United Nations Decade of Ocean Science for Sustainable Development (2021–2030) and the prospective extension of the IIOE-2 (2015–2020) well into the next decade will further motivate and catalyze opportunities for IndOOS. Data dissemination for operational applications should form a key part of any vision, as should end-user engagement, since, without a systematic approach to secure and disseminate *in situ* observations, stakeholder communities will not fully realize the payoff of *in situ* observing investments. The IndOOS review is a first step toward this but more involvement of program managers, rim countries and end users is essential.

CONCLUSION

The Indian Ocean Observing System, IndOOS, is a sustained basin-scale observing system, playing a key role as a major data source of the Indian Ocean. Under the decadal review of the Indian Ocean Observing System, a number of key recommendations have been made: Tier I relates to sustainment of the *essential* components of IndOOS, while streamlining the observing system in consideration of redundancy and logistical constraints; Tier II lists *priority* enhancements and Tier III lists *desirable* components. Although the full IndOOS review will be published in 2019, this paper has highlighted the key aspects of these tiers and the reasoning behind them, as well as giving an overview of some of the key regional and pilot programs which are providing much urgent data within a number of countries EEZs as well as developing key capacity in the region.

We have discussed the key areas of governance of IndOOS, as well as potential areas that can be strengthened to aid in the uptake of the data by end users, both in terms of scientists (e.g., calibration/validation, data analysis, data assimilation, and modeling) and policy makers (e.g., Indian Ocean Rim Association). The end user uptake of the data produced from IndOOS and the utility of IndOOS to decision-making needs considerable attention over the next decade, which will be addressed through the work of IndOOS and OceanObs'19 discussions.

AUTHOR CONTRIBUTIONS

JH, YM, LB, MR, and JV coordinated and led the overall writing of the manuscript, contributed with original research ideas, and gave substantial input into text and figures. All authors led various sections of the work with considerable input into the research ideas, review, and final text and figures.

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REFERENCES

Abram, N. J., Gagan, M. K., McCulloch, M. T., Chappell, J., and Hantoro, W. S. (2003). Coral reef death during the 1997 Indian Ocean Dipole linked to Indonesian wildfires. *Science* 301, 952–955. doi: 10.1126/science.1083841

Allison, E. H., Perry, A. L., Badjeck, M. C., and Adger, W. N. (2009). Vulnerability of national economies to the impacts of climate change on fisheries. *Fish Fish.* 10, 173–196. doi: 10.1111/j.1467-2979.2008.00310.x

Alory, G., Wijffels, S., and Meyers, G. (2007). Observed temperature trends in the Indian Ocean over 1960–1999 and associated mechanisms. *Geophys. Res. Lett.* 34:L02606.

Annamalai, H., Potemra, J., Murtugudde, R., and McCreary, J. P. (2005). Effect of preconditioning on the extreme climate events in the tropical Indian Ocean. *J. Clim.* 18, 3450–3469. doi: 10.1175/jcli3494.1

Ashok, K., Guan, Z., and Yamagata, T. (2003). Influence of the Indian Ocean Dipole on the Australian winter rainfall. *Geophys. Res. Lett.* 30, 1821. doi: 10.1029/2003GL017926

Ballabrera-Poy, J., Hackert, E., Murtugudde, R., and Busalacchi, A. J. (2007). An observing system simulation experiment for an optimal moored instrument array in the tropical Indian Ocean. *J. Clim.* 20, 3284–3299. doi: 10.1175/JCLI4149.1

Balmaseda, M. A., Hernandez, F., Storto, A., Palmer, M. D., Alves, O., Shi, L., et al. (2015). The ocean reanalysis intercomparison project (ORA-IP). *J. Oper. Oceanogr.* 8, 80–97. doi: 10.1080/1755876X.2015.1022329

Barange, M., Merino, G., Blanchard, J. L., Scholtens, J., Harle, J., Allison, E. H., et al. (2014). Impacts of climate change on marine ecosystem production in societies 137 dependent on fisheries. *Nat. Clim. Change* 4, 211–216. doi: 10.1038/nclimate2119

Beal, L. M., and Elipot, S. (2016). Broadening not strengthening of the Agulhas Current since the early 1990s. *Nature* 540:570. doi: 10.1038/nature19853

Beal, L. M., Elipot, S., Houk, A., and Leber, G. M. (2015). Capturing the transport variability of a western boundary jet: results from the agulhas current time-series experiment (ACT). *J. Phys. Oceanogr.* 45, 1302–1324. doi: 10.1175/jpo-d-14-0119.1

Beal, L. M., Hormann, V., Lumpkin, R., and Foltz, G. R. (2013). The response of the surface circulation of the Arabian Sea to monsoonal 877 forcing. *J. Phys. Oceanogr.* 43, 2008–2022. doi: 10.1175/jpo-d-13-033.1

Bellenger, H., and Duvel, J. P. (2009). An analysis of tropical ocean diurnal warm layers. *J. Clim.* 22, 3629–3646. doi: 10.1175/2008jcli2598.1

Bernie, D. J., Woolnough, S. J., Slingo, J. M., and Guilyardi, E. (2005). Modeling diurnal and intraseasonal variability of the ocean mixed layer. *J. Clim.* 18, 1190–1202. doi: 10.1175/jcli3319.1

Bindoff, N. L., and McDougall, T. J. (2000). Decadal changes along an Indian Ocean section at 32 S and their interpretation. *J. Phys. Oceanogr.* 30, 1207–1222. doi: 10.1175/1520-0485(2000)030

Bleck, R. (2002). An oceanic general circulation model framed in hybrid isopycnic-Cartesian coordinates. *Ocean Modell.* 4, 55–88. (accessed June 18, 2019).

Bristow, L. A., Callbeck, C. M., Larsen, M., Altabet, M. A., Dekaezemacker, J., Forth, M., et al. (2017). N 2 production rates limited by nitrite availability in the Bay of Bengal oxygen minimum zone. *Nat. Geosci.* 10:24. doi: 10.1038/ngeo2847

Broecker, W. S. (1991). The great ocean conveyor. *Oceanography* 4, 79–89. doi: 10.5670/oceanog.1991.07

Bryden, H. L., and Beal, L. M. (2001). Role of the agulhas current in indian ocean circulation and associated heat and freshwater fluxes. *Deep Sea Res. Part I* 48, 1821–1845. doi: 10.1016/s0967-0637(00)00111-4

Cai, W., Wu, L., Lengaigne, M., Li, T., McGregor, S., Kug, J.-S., et al. (2019). Pan-tropical climate interactions. *Science* 363:eaav4236. doi: 10.1126/science.aav4236

Carson, C., Kohl, A., and Stammer, D. (2015). The impact of regional multidecadal and century-scale internal climate variability on sea level trends in CMIP5. *J. Clim.* 28, 853–861. doi: 10.1175/JCLI-D-14-00359.1

Centurioni, L., Horányi, A., Cardinali, C., Charpentier, E., and Lumpkin, R. (2016). A global ocean 1988 observing system for measuring sea level atmospheric pressure: effects and impacts on 1989 numerical weather prediction. *Bull. Am. Meteorol. Soc.* 98, 231–238. doi: 10.1175/bams-d-15-00080.1

Chelton, D. B., Schlax, M. G., and Samelson, R. M. (2011). Global observations of nonlinear mesoscale eddies. *Prog. Oceanog.* 91, 167–216. doi: 10.1016/j.pocean.2011.01.002

Chen, G., Han, W., Shu, Y., Li, Y., Wang, D., and Xie, Q. (2016). The role of equatorial undercurrent in sustaining the Eastern Indian Ocean upwelling. *Geophys. Res. Lett.* 43, 6444–6451. doi: 10.1002/2016GL069433

Cheng, L., Trenberth, K., Fasullo, J., Boyer, T., Abraham, J., and Zhu, J. (2016). Improved estimates of ocean heat content from 1960 to 2015. *Sci. Adv.* 3:e1601545. doi: 10.1126/sciadv.1601545

Clarke, A. J., and Van Gorder, S. (2003). Improving El Nino prediction using a space-time integration of Indo-Pacific winds and equatorial Pacific upper ocean heat content. *Geophys. Res. Lett.* 30:1399. doi: 10.1029/2002GL016673

D'Arrigo, R., and Wilson, R. (2008). El Nino and Indian Ocean influences on Indonesian drought: 1342 implications for forecasting rainfall and crop productivity. *Int. J. Climatol.* 28, 611–616. doi: 10.1002/joc.1654

DeMott, C. A., Klingaman, N. P., and Woolnough, S. J. (2015). Atmosphere-ocean coupled processes in the Madden-Julian oscillation. *Rev. Geophys.* 53, 1099–1154. doi: 10.1002/2014RG000478

Desbruyères, D., McDonagh, E. L., King, B. A., and Thierry, V. (2017). Global and full-depth ocean temperature trends during the early 21st century from argo and repeat hydrography. *J. Clim.* 30, 1985–1997. doi: 10.1175/JCLI-D-16-0396

Dilmahamod, F., Hermes, J. C., and Reason, C. J. (2015). Chlorophyll-a variability in the seychelles-chagos thermocline ridge: analysis of a coupled biophysical model. *J. Mar. Syst* 154, 220–232. doi: 10.1016/j.jmarsys.2015.10.011

Doi, T., Storto, A., Behera, S. K., Navarra, A., and Yamagata, T. (2017). Improved prediction of the Indian ocean dipole mode by use of subsurface ocean observations. *J. Clim.* 30, 7953–7970. doi: 10.1080/1755876X.2015.1049883

Dombrowsky, E., Bertino, L., Brassington, G. B., Brassington, G. B., and Chassign, E. P. (2009). GODAE systems in operation. *Oceanography* 22, 80–95. doi: 10.5670/oceanog.2009.68

Dong, L., and McPhaden, M. J. (2017). Why has the relationship between Indian and Pacific Ocean decadal variability changed in recent decades? *J. Clim.* 30, 1971–1983. doi: 10.1175/jcli-d-16-0313.1

Durack, P. J., Lee, T., Vinogradova, N. T., and Stammer, D. (2016). Keeping the lights on for global ocean salinity observation. *Nat. Clim. Change* 6:228. doi: 10.1038/nclimate2946

Duvel, J. P., and Vialard, J. (2007). Indo-Pacific sea surface temperature perturbations associated with intraseasonal oscillations of tropical convection. *J. Clim.* 20, 3056–3082. doi: 10.1175/jcli4144.1

ESCAP (2018). *Asia and the Pacific Regional Expert Workshop on Ocean Accounts*. Bangkok: ESCAP. doi: 10.1175/jcli4144.1

Feng, M., Böning, C., Biastoch, A., Behrens, E., Weller, E., and Masumoto, Y. (2011). The reversal of the multi-decadal trends of the equatorial Pacific easterly winds, and the Indonesian throughflow and Leeuwin current transports. *Geophys. Res. Lett.* 38:L11604. doi: 10.1029/2011GL047291

Feng, M., Hendon, H. H., Xie, S.-P., Marshall, A. G., Schiller, A., Kosaka, Y., et al. (2015). Decadal increase in Ningaloo Niño since the late 1990s. *Geophys. Res. Lett.* 42, 104–112. doi: 10.1002/2014GL062509

Feng, M., Li, Y., and Meyers, G. (2004). Multidecadal variations of Fremantle sea level: footprint of climate variability in the tropical Pacific. *Geophys. Res. Lett.* 31:L16302. doi: 10.1029/2004GL019947

Feng, M., McPhaden, M. J., Xie, S.-P., and Hafner, J. (2013). La Niña forces unprecedented Leeuwin Current warming in 2011. *Sci. Rep.* 3:1277. doi: 10.1038/srep01277

Feng, R., Duan, W., and Mu, M. (2016). Estimating observing locations for advancing beyond the winter predictability barrier of Indian Ocean dipole event predictions. *Clim. Dyn.* 48:1173. doi: 10.1007/s00382-016-3134-3

Forget, G., Campin, J.-M., Heimbach, P., Hill, C. N., Ponte, R. M., and Wunsch, C. (2015). ECCO version 4: an integrated framework for non-linear inverse modeling and global ocean state estimation. *Geosci. Model Dev.* 8, 3071–3104. doi: 10.5194/gmd-8-3071-2015

Fujii, Y., Cummings, J., Xue, Y., Schiller, A., Lee, T., Balmaseda, M. A., et al. (2015). Evaluation of the tropical Pacific observing system from the ocean data assimilation perspective. *Q. J. R. Meteorol. Soc.* 141, 2481–2496. doi: 10.1002/qj.2579

Fukasawa, M., Freeland, H. J., Perkin, R., Watanabe, T., Uchida, H., and Nishina, A. (2004). Bottom water warming in the North Pacific Ocean. *Nature* 427, 825–827. doi: 10.1038/nature02337

Funk, C., Dettinger, M. D., Michaelsen, J. C., Verdin, J. P., Brown, M. E., Barlow, M., et al. (2008). Warming of the Indian Ocean threatens eastern and southern African food security but could be mitigated by agricultural development. *Proc. Natl. Acad. Sci. U.S.A.* 105, 11081–11086. doi: 10.1073/pnas.0708196105

Ganachaud, A., and Wunsch, C. (2000). Improved estimates of global ocean circulation, heat transport and mixing from hydrographic data. *Nature* 408, 453–457. doi: 10.1038/35044048

GEO (2017). *Highlights 2016-2017, Insight for a Changing World*. Available at: http://earthobservations.org/documents/geo_xiv/GEO%20Highlights%202016-2017.pdf (accessed June 18, 2019).

Giannini, A., Saravanan, R., and Chang, P. (2003). Oceanic forcing of Sahel rainfall on interannual to interdecadal time scales. *Science* 302, 1027–1030. doi: 10.1126/science.1089357

Godhe, A., Narayanaswamy, C., Klais, R., Venkatesha Moorthy, K. S., Ramesh, R., Rai, R., et al. (2015). Long-term patterns of net phytoplankton and hydrography in coastal SE Arabian Sea: what can be inferred from genus level data? *Estuar. Coast. Shelf Sci.* 162, 69–75. doi: 10.1016/j.ecss.2015.03.006

Gomes, H. D., Goes, J. I., Matondkar, S. G., Buskey, E. J., Basu, S., Parab, S., et al. (2014). Massive outbreaks of Noctiluca scintillans blooms in the Arabian Sea due to spread of hypoxia. *Nat. Commun.* 5:4862. doi: 10.1038/ncomms5862

Gordon, A. L., Sprintall, J., Van Aken, H. M., Susanto, R. D., Wijffels, S., Molcard, R., et al. (2010). The Indonesian throughflow during 2004-2006 as observed by the INSTANT program. *Dyn. Atmos. Oceans* 50, 115–128. doi: 10.1016/j.dynatmoce.2009.12.002

Gould, W., Roemmich, D., Wijffels, S., Freeland, H., Ignaszewsky, M., Jianping, X., et al. (2004). Argo profiling floats bring new era of in situ ocean observations. *Eos Trans. Am. Geophys. Union* 85, 185–191. doi: 10.1029/2004EO190002

Graham, N. E., and Barnett, T. P. (1987). Sea surface temperature, surface wind divergence, and convection over the tropical oceans. *Science* 238, 657–659. doi: 10.1126/science.238.4827.657

Griffies, S. M. (2012). *Elements of the Modular Ocean Model (MOM). GFDL Ocean Group Technical Report No.* 7. Silver Spring, MD: NOAA. doi: 10.1126/science.238.4827.657

Hamlington, B. D., Strassburg, M. W., Leben, R., Han, W., Nerem, R. S., and Kim, K. Y. (2014). Uncovering the anthropogenic warming-induced sea level rise signal in the Pacific Ocean. *Nat. Clim. Change* 4, 782–785. doi: 10.1038/s41598-017-00875-5

Han, W., Vialard, J., McPhaden, M. J., Lee, T., Masumoto, Y., Feng, M., et al. (2014). Indian ocean decadal variability: a review. *Bull. Am. Meteorol. Soc.* 95, 1679–1703. doi: 10.1016/bs.amb.2016.04.002

Harrison, D. E., and Vecchi, G. A. (2001). January 1999 Indian Ocean cooling event. *Geophys. Res. Lett.* 28, 3717–3720. doi: 10.1029/2001gl013506

Hermes, J., Pearlman, J., and Buttigieg, P. L. (2018). What's the best way to responsibly collect ocean data?. *Eos* 99. doi: 10.1029/2018EO096533

Hernández-Guerra, A., and Talley, L. D. (2016). Meridional overturning transports at 30 S in the Indian and Pacific Oceans in 2002–2003 and 2009. *Prog. Oceanogr.* 146, 89–120. doi: 10.1016/j.pocean.2016.06.005

Hoerling, M., Eischeid, J., Perlwitz, J., Quan, X., Zhang, T., and Pegion, P. (2012). On the increased frequency of mediterranean drought. *J. Clim.* 25, 2146–2161. doi: 10.1175/jcli-d-11-00296.1

Hoerling, M., Hurrell, J. W., Xu, T., Bates, G., and Phillips, A. (2004). Twentieth century north Atlantic climate change. Part II: understanding the effect of

Indian Ocean warming. *Clim. Dyn.* 23, 391–405. doi: 10.1007/s00382-004-0433-x

Hood, E. M., Sabine, C. L., and Sloyan, B. M. (eds) (2010). *The GO-SHIP Repeat Hydrography Manual: A Collection of Expert Reports and Guidelines. IOCCP Report Number 14. ICPO Publication Series Number 134.* Available at: http://www.go-ship.org/HydroMan.html (accessed June 18, 2019).

Hood, R. R., Bange, H. W., Beal, L., Beckley, L. E., Burkill, P., Cowie, G. L., et al. (2015). *The Second International Indian Ocean Expedition (IIOE-2): A Basin-Wide Research Program-Science Plan (2015–2020)*. Newark, NJ: Scientific Committee on Oceanic Research. Available at: https://www.oceandocs.org/handle/1834/9675 (accessed June 18, 2019).

Hood, R. R., Kohler, K. E., McCreary, J. P., and Smith, S. L. (2003). A four-dimensional validation of a coupled physical-biological model of the Arabian Sea. *Deep Sea Res. II* 50, 2917–2945. doi: 10.1016/j.dsr2.2003.07.004

Hu, S., and Sprintall, J. (2017). Observed strengthening of interbasin exchange via the Indonesian seas due to rainfall intensification. *Geophys. Res. Lett.* 44, 1448–1456. doi: 10.1002/2016GL072494

Huang, K., Han, W., Wang, D., Wang, W., Xie, Q., Chen, J., et al. (2018a). Features of the equatorial intermediate current associated with basin resonance in the Indian Ocean. *J. Phys. Oceanogr.* 48, 1333–1347. doi: 10.1175/JPO-D-17-0238.1

Huang, K., McPhaden, M. J., Wang, D. X., Wang, W. Q., Xie, Q., Chen, J., et al. (2018b). Vertical propagation of mid-depth zonal currents associated with surface wind forcing in the equatorial Indian Ocean. *J. Geophys. Res. Oceans* 123, 7290–7307. doi: 10.1029/2018JC013977

Huang, K., Wang, D., Wang, W., Xie, Q., Chen, J., Chen, L., et al. (2018c). Multi-scale variability of the tropical Indian Ocean circulation system revealed by recent observations. *Sci. China Earth Sci.* 61, 668–680. doi: 10.1007/s11430-017-9179-x

Intergovernmental Panel on Climate Change [IPCC] (2013). *IPCC WGI Fifth Assessment Report*. Geneva: IPCC. doi: 10.1007/s11430-017-9179-x

Iskandar, I., Mardiansyah, W., Masumoto, Y., and Yamagata, T. (2005). Intraseasonal Kelvin waves along the southern coast of Sumatra and Java. *J. Geophys. Res.* 110:C04013. doi: 10.1029/2004JC002508

Izumo, T., de Boyer Montégut, C., Luo, J. J., Behera, S. K., Masson, S., and Yamagata, T. (2008). The role of the western Arabian Sea upwelling in Indian monsoon rainfall variability. *J. Clim.* 21:5623.

Izumo, T., Jerome, V., Matthieu, L., Behera Swadhin, K., Jing-Jia, L., Sophie, C., et al. (2010). Influence of the state of the Indian Ocean dipole on following year's El Ninþo. *Nat. Geosci.* 3, 168–172. doi: 10.1038/ngeo

Jeong, H. I., Ahn, J. B., Lee, J. Y., Alessandri, A., and Hendon, H. H. (2015). Interdecadal change of interannual variability and predictability of two types of ENSO. *Clim. Dyn.* 44, 1073–1091. doi: 10.1007/s00382-014-2127-3

Jickells, T. D., Buitenhuis, E., Altieri, K., Buitenhuis, E., Altieri, K., Baker, A. R., et al. (2017). A reevaluation of the magnitude and impacts of anthropogenic atmospheric nitrogen inputs on the Ocean. *Glob. Biogeochem. Cycl.* 31, 289–305.

Johns, W. E., Baringer, M. O., Beal, L. M., Cunningham, S. A., Kanzow, T., Bryden, H. L., et al. (2011). Continuous, array-based estimates of Atlantic Ocean heat transport at 26.5 *N. J. Clim.* 24, 2429–2449. doi: 10.1175/2010jcli3997.1

Johnson, G. C., Purkey, S. G., and Bullister, J. L. (2008). Warming and freshening in the abyssal southeastern Indian Ocean. *J. Clim.* 21, 5351–5363. doi: 10.1175/2008JCLI2384.1

Johnson, K., and Claustre, H. (2016). The scientific rationale, design and implementation plan for a biogeochemical-argo float array. *Biogeochem. Argo Plann. Group* 58:65. doi: 10.13155/46601

Kaur-Kahlon, G., Kumar, S., Rehnstam-Holm, A.-S., Rai, A., Bhavya, P. S., Edler, L., et al. (2016). Response of a coastal tropical pelagic microbial community to changing salinity and temperature. *Aqu. Microb. Ecol.* 77, 37–50. doi: 10.3354/ame01785

Kumar, S., Bhavya, P. S., Ramesh, R., Gupta, G. V. M., Chiriboga, F., Singh, A., et al. (2018). Nitrogen uptake potential under different temperature-salinity conditions: implications for nitrogen cycling under climate change scenarios. *Mar. Environ. Res.* 141, 196–204. doi: 10.1016/j.marenvres.2018.09.001

Lee, S.-K., Park, W., Baringer, M. O., Gordon, A., Huber, B., and Liu, Y. (2015). Pacific origin of the abrupt increase in Indian Ocean heat content during the warming hiatus. *Nat. Geosci.* 8, 445–450.

Lee, T., Awaji, T., Balmaseda, M. A., Greiner, E., and Stammer, D. (2009). Ocean state estimation for climate research. *Oceanography* 22, 160–167. doi: 10.5670/oceanog.2009.74

Legler, D. M., Freeland, H. J., Lumpkin, R., Ball, G., McPhaden, M. J., North, S., et al. (2015). The current status of the real-time in situ Global Ocean observing system for operational oceanography. *J. Oper. Oceanogr.* 8(Suppl. 2), s189–s200. doi: 10.1080/1755876x.2015.1049883

Liu, H., Tang, Y., Chen, D., and Lian, T. (2017). Predictability of the Indian ocean dipole in the coupled models. *Clim. Dyn.* 48, 2005–2024. doi: 10.1038/nature13327

Lumpkin, R., and Speer, K. (2007). Global ocean meridional overturning. *J. Phys. Oceanogr.* 37, 2550–2562. doi: 10.1175/jpo3130.1

Luo, J.-J., Behera, S., Masumoto, Y., Sakuma, H., and Yamagata, T. (2008). Successful prediction of the consecutive IOD in 2006 and 2007. *Geophys. Res. Lett.* 35:L14S02. doi: 10.1029/2007GL032793

Luo, J.-J., Sasaki, W., and Masumoto, Y. (2012). Indian Ocean warming modulates Pacific climate change. *Proc. Natl. Acad. Sci.* 109, 18701–18706. doi: 10.1073/pnas.1210239109

Luo, J.-J., Zhang, R., Behera, S. K., Masumoto, Y., Jin, F.-F., Lukas, R., et al. (2010). Interaction between El Niño and Extreme Indian Ocean Dipole. *J. Clim.* 23, 726–742. doi: 10.1175/2009JCL13104.1

Marshall, J., Adcroft, A., Hill, C., Perelman, L., and Heisey, C. (1997). A finite-volume, incompressible Navier-Stokes model for studies of the ocean on parallel computers. *J. Geophys. Res.* 102, 5753–5766. doi: 10.1029/96jc02775

Masumoto, Y. (2010). Sharing results of a high-resolution ocean general circulation model under multi-discipline framework - A review of OFES activities. *Ocean Dyn.* 60, 633–652. doi: 10.1007/s10236-010-0297-z

Masumoto, Y., Yu, W., Meyers, G., D'Adamo, N., Beal, L., de Ruijter, W. P. M., et al. (2010). "Observing systems in the Indian Ocean," in *Proceedings of the "OceanObs'09: Sustained Ocean Observations and Information for Society" Conference*, Vol. 2, eds J. Hall, D. E. Harrison, and D. Stammer (Venice: ESA Publication WPP), 306.

Maximenko, N., Niiler, P., Rio, M.-H., Melnichenko, O., Centurioni, L., Chambers, D., et al. (2009). Mean dynamic topography of the ocean derived from satellite and drifting buoy data using three different techniques. *J. Atmos. Ocean. Technol.* 26, 1910–1919. doi: 10.1175/2009JTECHO672.1

McDonagh, E. L., Bryden, H. L., King, B. A., Sanders, R. J., Cunningham, S. A., and Marsh, R. (2005). Decadal changes in the South Indian Ocean thermocline. *J. Clim.* 18, 1575–1590. doi: 10.1038/s41598-019-43841-z

McPhaden, M. J., Ando, K., Bourlès, B., Freitag, H. P., Lumpkin, R., Masumoto, Y., et al. (2010). "The global tropical moored buoy array," in *Proceedings of the "OceanObs'09: Sustained Ocean Observations and Information for Society" Conference*, Vol. 2, eds J. Hall, D. E. Harrison, and D. Stammer (Venice.: ESA Publication WPP), 306.

McPhaden, M. J., Meyers, G., Ando, K., Masumoto, Y., Murty, V. S. N., Ravichandran, M., et al. (2009). RAMA: The research moored array for African-Asian-Australian monsoon analysis and prediction. *Bull. Am. Meteorol. Soc.* 90, 459–480. doi: 10.1175/2008BAMS2608.1

Meyers, G., Bailey, R. J., and Worby, A. P. (1995). Geostrophic transport of Indonesian throughflow. *Deep Sea Res.* 42, 1163–1174. doi: 10.1016/0967-0637(95)00037-7

Miloslavich, P., Pax, N. J., Simmons, S. E., Klein, E., Appeltans, W., Aburto-Oropeza, O., et al. (2018). Essential ocean variables for global sustained observations of biodiversity and ecosystem changes. *Glob. Change Biol.* doi: 10.1111/gcb.14108 [Epub ahead of print].

Morris, T., Hermes, J., Beal, L., Du Plessis, M., Rae, C. D., Gulekana, M., et al. (2017). The importance of monitoring the greater agulhas current and its inter-ocean exchanges using large mooring arrays. *S. Afr. J. Sci.* 113, 1–7. doi: 10.17159/sajs.2017/20160330

Naqvi, S. W. A., Bange, H. W., Farías, L., Monteiro, P. M. S., Scranton, M. I., Zhang, J., et al. (2010). Marine hypoxia/anoxia as a source of CH4 and N2O. *Biogeoscience* 7, 2159–2190. doi: 10.5194/bg-7-2159-2010

Neetu, S., Lengaigne, M., Vialard, J., Samson, G., Masson, S., Krishnamohan, K. S., et al. (2019). Premonsoon/Postmonsoon Bay of Bengal tropical cyclones intensity: role of air-sea coupling and large-scale background state. *Geophys. Res. Lett.* 45, 2149–2157. doi: 10.1029/2018gl081132

Nicholls, R. J., and Cazenave, A. (2010). Sea-level rise and its impact on coastal zones. *Science* 328, 1517–1520. doi: 10.1126/science.1185782

Obura, D. (2017). *Reviving the Western Indian Ocean Economy: Actions for a Sustainable Future*. Gland: WWF International, 64.

OECD (2016). *The Ocean Economy in 2030*. Paris: OECD Publishing.

Oke, P. R., and Schiller, A. (2007). A model-based assessment and design of a tropical indian ocean mooring array. *J. Clim.* 20, 3269–3283. doi: 10.1175/JCLI4170.1

Palmer, D. H., Bryden, H. L., Hirschi, J., and Marotzke, J. (2004). Observed changes in the South Indian Ocean gyre circulation, 1987-2002. *Geophys. Res. Lett.* 31:L15303. doi: 10.1029/2004GL020506

Paterson, A., Hermes, J., Bornman, T., Klarenbeek, T., Siko, G., and Palmer, R. (2018). *A compendium of South African Research in the Western Indian Ocean*. Johannesburg: University of Johannesburg.

Prasanna Kumar, S., Madhupratap, M., Dileepkumar, M., Muraleedharan, P., DeSouza, S., Gauns, M., et al. (2001). High biological productivity in the central Arabian Sea during the summer monsoon driven by Ekman pumping and lateral advection. *Curr. Sci.* 81, 1633–1638.

Prasanna Kumar, S., Muraleedharen, P. M., Thoppil, P., Madhupratap, M., Gaumns, M., Nagappa, R., et al. (2002). Why Bay of Bengal is less productive during summer monsoon compared to the Arabian Sea? *Geophys. Res. Lett.* 29, 88–81. doi: 10.1029/2002GL016013

Purkey, S. G., and Johnson, G. C. (2010). Warming of global abyssal and deep Southern Ocean waters between the 1990s and 2000s: contributions to global heat and sea level rise budgets. *J. Clim.* 23, 6336–6353. doi: 10.1175/2010JCLI3682

Purkey, S. G., and Johnson, G. C. (2013). Antarctic bottom water warming and freshening: contributions to sea level rise, ocean freshwater budgets, and global heat gain. *J. Clim.* 26, 6105–6122. doi: 10.1175/JCLI-D-12-00834.1

Reason, C. J. C. (2001). Subtropical Indian Ocean dipole events and southern African rainfall. *Geophys. Res. Lett.* 28, 2225–2227. doi: 10.1029/2000gl012735

Roberts, C. D., Palmer, M. D., Allan, R. P., Desbruyeres, D. G., Hyder, P., Liu, C., et al. (2017). Surface flux and ocean heat transport convergence contributions to seasonal and interannual variations of ocean heat content. *J. Geophys. Res. Oceans* 122, 726–744. doi: 10.1002/2016jc012278

Roxy, M. K., Raghu Murtugudde, A. M., Valsala, V., Panickal, S., Prasanna Kumar, S., Ravichandran, M., et al. (2016). A reduction in marine primary productivity driven by rapid warming over the tropical Indian Ocean. *Geophys. Res. Lett.* 43, 826–833. doi: 10.1002/2015gl066979

Saji, N. H., Goswami, B. N., Vinayachandran, P. N., and Yamagata, T. (1999). A dipole mode in the tropical Indian Ocean. *Nature* 401, 360–363. doi: 10.1038/43854

Saji, N. H., Xie, S.-P., and Tam, C. Y. (2006). Satellite observations of intense intraseasonal cooling events in the tropical south Indian Ocean. *Geophys. Res. Lett.* 33:L14704. doi: 10.1029/2006GL026525

Schott, F., and McCreary, J. P. (2001). The monsoon circulation of the Indian Ocean. *Prog. Oceanogr.* 51, 1–123. doi: 10.1016/s0079-6611(01)00083-0

Schott, F. A., Xie, S.-P., and McCreary, J. P. (2009). Indian Ocean circulation and climate variability. *Rev. Geophys.* 47:RG1002. doi: 10.1029/2007RG000245

Seo, H., Subramanian, A. C., Miller, A. J., and Cavanaugh, N. R. (2014). Coupled impacts of the diurnal cycle of sea surface temperature on the Madden–Julian oscillation. *J. Clim.* 27, 8422–8443. doi: 10.1175/jcli-d-14-00141.1

Shchepetkin, A. F., and McWilliams, J. C. (2005). The regional ocean modeling system: a split-explicit, free-surface, topography following coordinates ocean model. *Ocean Model.* 9, 347–404. doi: 10.1016/j.ocemod.2004.08.002

Shenoi, S. S. C., Shankar, D., and Shetye, S. R. (2002). Differences in heat budgets of the 87 near surface Arabian Sea and Bay of Bengal: Implications for the summer monsoon. *J. Geo. Phys.* 107, 5-1–5-14. doi: 10.1029/2000JC000679

Shinoda, T. (2005). Impact of diurnal cycle of solar radiation on intraseasonal SST variability in the western equatorial Pacific. *J. Clim.* 18, 2628–2636. doi: 10.1175/jcli3432.1

Shinoda, T., and Hendon, H. H. (1998). Mixed layer modeling of intraseasonal variability in the tropical western Pacific and Indian oceans. *J. Clim.* 11, 2668–2685. doi: 10.1175/1520-0442(1998)011

Singh, A., and Ramesh, R. (2015). Environmental controls on new and primary production in the Northern Indian Ocean. *Prog. Oceanogr.* 131, 138–145. doi: 10.1016/j.pocean.2014.12.006

Song, Q., Vecchi, G. A., and Rosati, A. J. (2008). Predictability of the Indian Ocean sea surface temperature anomalies in the GFDL coupled model. *Geophy. Res. Lett.* 35:L02701. doi: 10.1029/2007GL031966

Sprintall, J., Gordon, A. L., Koch-Larrouy, A., Lee, T., Potemra, J. T., Pujiana, K., et al. (2014). The Indonesian seas and their role in the coupled ocean-climate system. *Nat. Geosci.* 7, 487–492. doi: 10.1038/ngeo2188

Sprintall, J., and Révelard, A. (2014). The Indonesian throughflow response to Indo-Pacific climate variability. *J. Geophys. Res.* 119, 1161–1175. doi: 10.1002/2013JC009533

Sprintall, J., Wijffels, S., Chereskin, T., and Bray, N. (2002). The JADE and WOCE I10/IR6 2059 Throughflow Sections in the Southeast Indian Ocean. Part 2: velocity and transports. *Deep sea Res. Part II* 49, 1363–1389. doi: 10.1016/s0967-0645(01)00163-1

Sprintall, J., Wijffels, S. E., Molcard, R., and Jaya, I. (2009). Direct estimates of the Indonesian 987 throughflow entering the Indian Ocean: 2004-2006. *J. Geophys. Res.* 114:C07001. doi: 10.1029/2008JC005257

Strutton, P. G., Coles, V. J., Hood, R. R., Matear, R. J., McPhaden, M. J., and Phillips, H. E. (2015). Biogeochemical variability in the central equatorial Indian Ocean during the monsoon transition. *Biogeosciences* 12, 2367–2382. doi: 10.5194/bg-12-2367-2015

Takahashi, T., Sutherland, S. C., Sweeney, C., Poisson, A., Metzl, N., Tilbrook, B., et al. (2002). 'Global sea-air CO2 flux based 860 on climatological surface ocean pCO2, and seasonal biological and temperature effects'. *Deep Sea Res. Part II* 49, 1601–1623.

Tanizaki, C., Tozuka, T., Doi, T., and Yamagata, T. (2017). Relative importance of the processes contributing to the development of SST anomalies in the eastern pole of the Indian Ocean Dipole and its implication for predictability. *Clim. Dyn.* 49, 1289–1304. doi: 10.1007/s00382-016-3382-2

Terray, P., Masson, S., Prodhomme, C., Roxy, M. K., and Sooraj, K. P. (2015). Impacts of Indian and Atlantic oceans on ENSO in a comprehensive modeling framework. *Clim. Dyn.* 46, 2507–2533. doi: 10.1007/s00382-015-2715-x

Task Team for an Integrated Framework for Sustained Ocean Observing (2012). *A Framework for Ocean Observing. IOC/INF*-1284 rev.2. Paris: UNESCO. doi: 10.1007/s00382-016-3382-2

U. N. Statistics Division (2018). *Sustainable Development Goal Indicators*. Available at: https://unstats.un.org/sdgs/ (accessed June 18, 2019).

Ummenhofer, C. C., Biastoch, A., and Böning, C. W. (2017). Multidecadal Indian Ocean Variability linked to the pacific and implications for preconditioning indian ocean dipole events. *J. Clim.* 30, 1739–1751. doi: 10.1175/jcli-d-16-0200.1

Ummenhofer, C. C., England, M. H., Meyers, G. A., McIntosh, P. C., Pook, M. J., Risbey, J. S., et al. (2009). What causes Southeast Australia's worst droughts? *Geophys. Res. Lett.* 36:L04706. doi: 10.1029/2008GL036801

UNGA (2015). *Transforming Our World: the 2030 Agenda for Sustainable Development*. New York, NY: UNGA.

United Nations (2018a). *System for Environmental Economic Accounting*. New York, NY: United Nations.

United Nations (2018b). *Framework for Development of Environment Statistics*. New York, NY: United Nations.

United Nations, European Commission, International Monetary Fund, Organisation for Economic Co-operation and Development, and World Bank (2008). *System of National Accounts 2008*. Available at: https://unstats.un.org/unsd/nationalaccount/sna2008.asp (accessed June 18, 2019).

Vecchi, G. A., and Harrison, M. J. (2007). An observing system simulation experiment for the Indian Ocean. *J. Clim.* 20, 3300–3319. doi: 10.1155/2014/314134

Vialard, J., Drushka, K., Bellenger, H., Lengaigne, M., Pous, S., and Duvel, J.-P. (2013). Understanding Madden-Julian-induced sea surface temperature variations in the North Western Australian Basin. *Clim. Dyn.* 41, 3203–3218. doi: 10.1007/s00382-012-1541-7

Vialard, J., Duvel, J. P., Mcphaden, M. J., Bouruet-Aubertot, P., Ward, B., and Key, E. (2009). Cirene: air sea interactions in the Seychelles-Chagos thermocline ridge region. *Bull. Am. Meterol. Soc.* 90, 45–61.

Vialard, J., Foltz, G. R., McPhaden, M. J., Duvel, J.-P., and de Boyer Montegut, C. (2008). Strong Indian Ocean sea surface temperature signals associated with the Madden-Julian Oscillation in late 2007 and early 2008. *Geophys. Res. Lett.* 35, 1–5.

Vialard, J., Jayakumar, A., Gnanaseelan, C., Lengaigne, M., Sengupta, D., and Goswami, B. N. (2012). Processes of 30–90 days sea surface temperature variability in the northern Indian Ocean during boreal summer. *Clim. Dyn.* 38, 1901–1916. doi: 10.1007/s00382-011-1015-3

Vitart, F., and Robertson, A. W. (2018). The sub-seasonal to seasonal prediction project (S2S) and the prediction of extreme events. *Clim. Atmos. Sci.* 1:3. doi: 10.1038/s41612-018-0013-0

Waite, A. M., Thompson, P. A., Beckley, L. E., and Feng, M. (2007). The leeuwin current and its eddies. *Deep Sea Res II* 54, 789–796. doi: 10.1371/journal.pone.0145822

Wajsowicz, R. C. (2005). Potential predictability of tropical Indian Ocean SST anomalies. *Geophys. Res. Lett.* 32:L24702. doi: 10.1029/2005GL024169

Webster, P. J., Moore, A. M., Loschnigg, J. P., and Leben, R. R. (1999). Coupled ocean–atmosphere dynamics in the Indian Ocean during 1997-98. *Nature* 401, 356–360. doi: 10.1038/43848

Wiggert, J. D., Murtugudde, R. G., and Christian, J. R. (2006). Annual ecosystem variability in the tropical Indian Ocean: results of a coupled bio-physical ocean general circulation model. *Deep Sea Res. II* 53, 644–676. doi: 10.1016/j.dsr2.2006.01.027

Wijffels, S. E., Meyers, G., and Godfrey, J. S. (2008). A 20-yr average of the Indonesian Throughflow: Regional currents and the interbasin exchange. *J. Phys. Oceanogr.* 38, 1965–1978. doi: 10.1175/2008jpo3987.1

Wu, L., Cai, W., Zhang, L., Nakamura, H., Timmermann, A., Joyce, T., et al. (2012). Enhanced warming over the global subtropical western boundary currents. *Nat. Clim. Change* 2:161. doi: 10.1038/nclimate1353

Wyrtki, K. (1973). An equatorial jet in the Indian Ocean. *Science* 181, 262–264. doi: 10.1126/science.181.4096.262

Xie, S.-P., Hu, K., Hafner, J., Tokinaga, H., Du, Y., Huang, G., et al. (2009). Indian Ocean capacitor effect on Indo–Western Pacific climate during the summer following El Niño. *J. Clim.* 22, 730–747. doi: 10.1175/2008jcli2544.1

Yamagata, T., Behera, S. K., Luo, J.-J., Masson, S., Jury, M. R., and Rao, S. A. (2004). "Coupled ocean-693 atmosphere variability in the tropical Indian Ocean," in *Earth's Climate: The Ocean-Atmosphere 694 Interaction. Geophys. Monogr. Ser*, Vol. 147, eds C. Wang, S.-P. Xie, and J. Carton (Washington, D. C: AGU), 189–211. doi: 10.1029/147gm12

Yang, Y., Xie, S.-P., Wu, L., Kosaka, Y., Lau, N.-C., and Vecchi, G. A. (2015). Seasonality and predictability of the Indian ocean dipole mode: ENSO forcing and internal variability. *J. Clim.* 28, 8021–8036. doi: 10.1175/JCLI-D-15-0078.1

Yu, L. (2019). Global air-sea fluxes of heat, freshwater, and momentum: energy budget closure and unanswered questions. *Annu. Res. Mar. Sci* 11, 227–248. doi: 10.1146/annurev-marine-010816-060704

Zhang, C. (2005). Madden-Julian oscillation. *Reviews of Geophysics* 43:RG2003. doi: 10.1029/2004RG000158

Zhang, Y., Feng, M., Du, Y., Phillips, H. E., Bindoff, N. L., and McPhaden, M. J. (2018). Strengthened Indonesian throughflow drives decadal warming in the Southern Indian Ocean. *Geophys. Res. Lett.* 45, 6167–6175.

Zhao, M., and Hendon, H. H. (2009). Representation and prediction of the Indian Ocean dipole in the POAMA seasonal forecast model. *Q. J. R. Meteorol. Soc.* 135, 337–352. doi: 10.1002/qj.370

Zhao, M., Hendon, H. H., Alves, O., Liu, G., and Wang, G. (2016). Weakened Eastern Pacific El Niño Predictability in the early twenty-first century. *J. Clim.* 29, 6805–6822. doi: 10.1175/jcli-d-15-0876.1

Zhu, J. B., Kumar, H. A., and Kinter, J. L. III (2015). Seasonality in prediction skill and predictable pattern of tropical Indian Ocean SST. *J. Clim.* 28, 7962–7984. doi: 10.1175/JCLI-D-15-0067.1

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REVIEW
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A Global Ocean Observing System (GOOS), Delivered Through Enhanced Collaboration Across Regions, Communities, and New Technologies

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Since OceanObs'09, the Global Ocean Observing System (GOOS) has evolved from its traditional focus on the ocean's role in global climate. GOOS now also encompasses operational services and marine ecosystem health, from the open ocean into coastal environments where much of the world's population resides. This has opened a field of opportunity for new collaborations—across regions, communities, and technologies—facilitating enhanced engagement in the global ocean observing enterprise to benefit all nations. Enhancement of collaboration is considered from the perspectives of regional alliances, global networks, national systems, *in situ* observing, remote sensing, oceanography, and meteorology. Reinvigoration of GOOS Regional Alliances has been important in connecting the power of this expanded remit to the needs of coastal populations and the capabilities of regional and national marine science communities. An assessment of progress is provided, including issues/challenges with the current structure, and opportunities to increase participation and impact. Meeting the expanded requirements of GOOS will entail new system networks. The Joint Technical Commission for Oceanography and Marine Meteorology Observations Coordination Group has been working with some communities to help assess their readiness, including high frequency radars, ocean gliders, and animal tracking. Much more needs to be done, with a range of strategies considered. Other opportunities include partnering with programs such as the Global Ocean Acidification Observing Network, engaging with mature and emerging national ocean observing programs, and learning from multinational projects such as Tropical Pacific Observing System 2020 and AtlantOS, which are bringing renewed rigor to the design and operation of regional observing systems. Consideration is given to the expansion and advancement that is coming in both *in situ* and remote sensing ocean observation platforms over the next decade. In combination they provide the potential to measure new Essential Ocean Variables routinely at global scale. Opportunities provided by the World Meteorological Organization Integrated Global Observing System (WIGOS) in fostering a comprehensive and integrated approach across meteorology and oceanography are also considered. The focus of WIGOS on providing accurate, reliable and timely weather, climate, and related environmental observations and products sits well with the expanded requirements of GOOS, in climate, operational services, and marine ecosystem health.

Keywords: GOOS, GRAs, WIGOS, satellite, networks, coastal, data, national

THE CHANGING CONTEXT FOR GOOS – FROM OceanObs'09 TO OceanObs'19

The genesis of the Global Ocean Observing System (GOOS) lies in the need to understand the ocean's role in global climate. In response to calls from the Second World Climate Conference, the Intergovernmental Oceanographic Commission (IOC) created GOOS in March 1991 (Jager and Ferguson, 1991). The first International Conference on the Ocean Observing System for Climate was held in San Rafael, France in October 1999 ('OceanObs'99') (Drinkwater et al., 1999).

Tremendous progress was made in our ability to observe the ocean globally between the creation of GOOS in 1991 and the second International Conference on Ocean Observing held in Venice in September 2009 (OceanObs'09) (Anderson, 2010). Examples include the Argo global profiling float array and virtual constellations of satellites measuring sea surface temperature, ocean color, ocean surface topography, and ocean surface vector winds.

Notwithstanding these achievements, implementation of GOOS *in situ* networks had plateaued at approximately 60% of design by the late 2000s (**Figure 1**).

Recognizing that GOOS needed to address requirements beyond the ocean's role in global climate, a key recommendation from OceanObs'09 was for international integration and coordination of interdisciplinary ocean observations. The OceanObs'09 sponsors commissioned a Task Team to respond to this challenge, leading to the development of *A Framework for Ocean Observing*, released in 2012 (Lindstrom et al., 2012).

The Framework for Ocean Observing applied a systems approach to sustained global ocean observing. It used Essential Ocean Variables (EOVs) as the common focus and defined the system based on requirements, observations, and data and information as the key components. Importantly it incorporated both coastal and open ocean observations. Assessment of feasibility, capacity, and impact for each of the three system components was based on readiness levels, i.e., concept, pilot, and mature.

It is the expansion of requirements for GOOS beyond weather and climate that is most significant in the context of this paper. Regional and global ocean assessments, fisheries management, ecosystem services, and real-time services have become drivers for GOOS over the last decade (**Figure 2**).

Global Ocean Observing System now seeks to coordinate observations around the global ocean for three critical themes: climate, operational services, and marine ecosystem health (GOOS, 2018a). This has opened up a field of opportunity for new collaborations to be formed—across regions, communities, and technologies—facilitating much enhanced engagement in the global ocean observing enterprise.

The governance of GOOS needed to change in response to these expanded requirements; therefore, a three-tiered governance model was implemented. A multinational steering committee was established to provide oversight (tier one). Scientific expert panels were formed to guide system requirements. Pre-existing structures were evolved to create discipline-based panels, providing scientific oversight on physics, biogeochemistry, and biology/ecosystems (tier two). Efforts were also made to connect with observation coordination groups involved in implementation at global and regional scales (tier three): the Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM), Observations Coordination Group (OCG), and the GOOS Regional Alliance (GRA) Council. The Chairs of JCOMM OCG and the GRA Council became ex-officio members of the GOOS Steering Committee. Finite lifetime observing system development projects (called GOOS pilot projects) were also introduced as a way of increasing the readiness of the observing system. Under this revised governance model, the GOOS Project Office has responsibility for facilitating collaboration between the three tiers.

In this paper we discuss progress in enhancing collaboration to meet the expanded requirements of GOOS in climate,

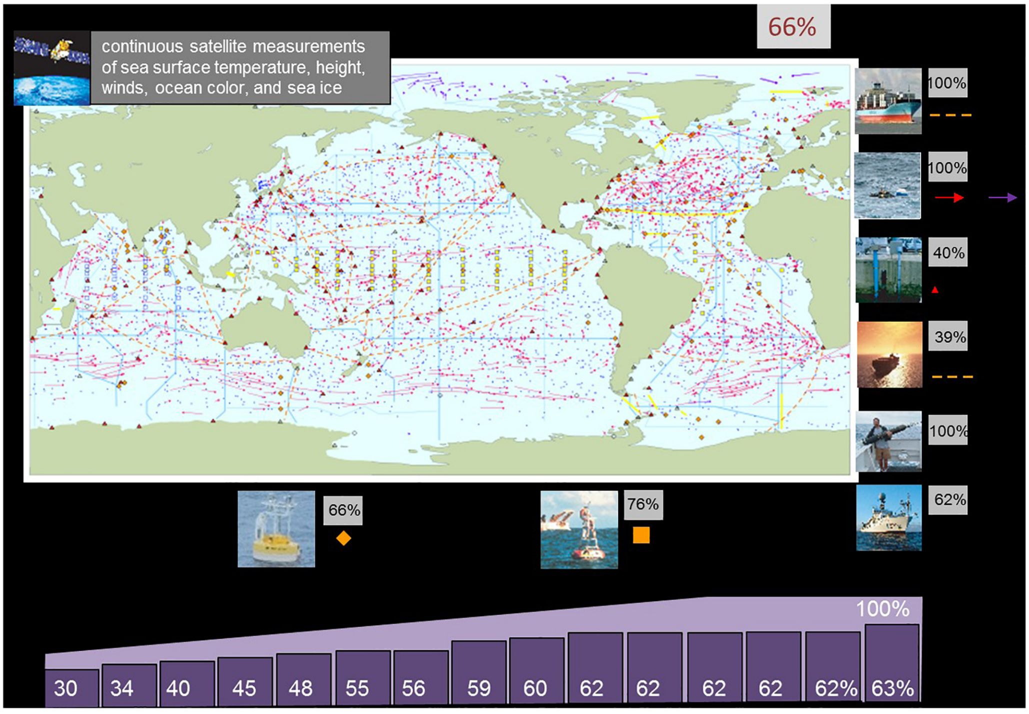


FIGURE 1 | Implementation of GOOS *in situ* networks versus 'design' (IOC-UNESCO, 2018).

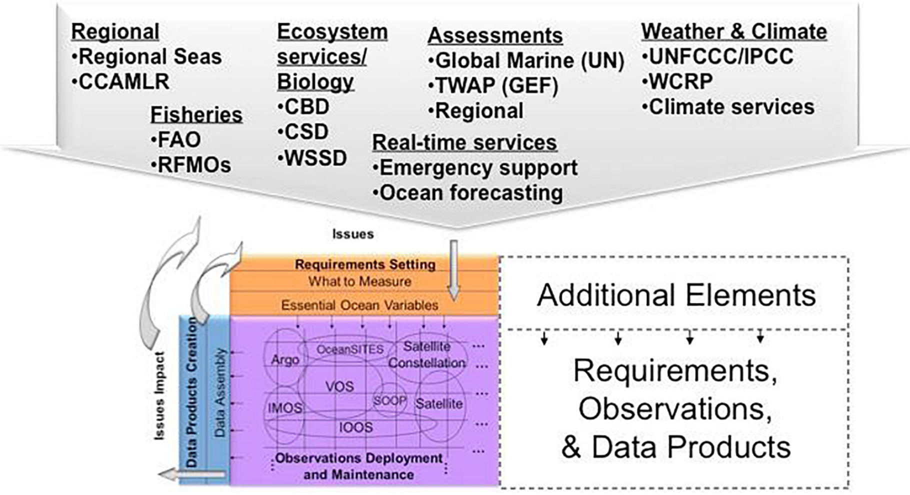


FIGURE 2 | Framework for Ocean Observing, societal drivers for the next decade (Lindstrom et al., 2012).

operational services, and marine ecosystem health. Collaboration is considered among national systems, regional alliances, and global networks, *in situ* observing and remote sensing, and oceanography and meteorology.

The role of GRAs is considered in Section "Think Global, Act Local – Challenges and Opportunities in Collaborating Across GOOS Regional Alliances." GRAs are particularly important for incorporating both coastal and open ocean observations, and for engaging with the users of operational services and the beneficiaries of marine ecosystem health. Efforts to build capacity within the GRA Council since OceanObs'09 are ongoing.

The need for GOOS to embrace new observations and data is considered in Section "The Need for New Observations and Biological and Coastal Data to Meet Expanded Requirements for GOOS." The expanded requirements of GOOS in 2019 will not be met by a system designed in the 1990s. New EOVs for biogeochemistry (e.g., oxygen), and biology/ecosystems (e.g., zooplankton biomass and diversity, fish distribution, and abundance), need to be measured by platforms and sensors with the requisite level of technological readiness. Expanding spatial coverage of physical observing into coastal oceans requires additional technologies [e.g., high frequency (HF) radars, ocean gliders]. Global coordination of these additional networks presents a challenge for JCOMM OCG and others. That said, the fact that several GRAs are already operating some of these networks provides a basis for multinational coordination that can be leveraged. Partnerships with programs such as the Global Ocean Acidification Observing Network (GOA-ON) and other programs centered around EOVs rather than platforms provide another opportunity. The need for new data and information systems and products is also a significant issue.

The importance of harnessing national efforts is considered in Section "Harnessing the Power of National Capabilities and Multinational Collaborations." Most investment in global ocean observing comes through national programs and to some extent has been engaged through the GRA Council and JCOMM OCG (e.g., in the United States, Australia, and Europe). In other cases, mature and emerging national programs have not yet been engaged in GOOS through existing intergovernmental mechanisms (e.g., in India, Canada, South Africa). In addition, multinational projects such as Tropical Pacific Observing System (TPOS) 2020 and AtlantOS are redesigning regional observing systems to enhance integration and fully leverage all available ocean observing technologies. How these redesigned systems are governed on an ongoing basis will be significant in a GRA context. Harnessing national efforts and regional collaborations is considered to be a major opportunity for GOOS in the coming decade.

In Section "GOOS as a Mechanism for Partnership Between Global Satellite and *in situ* Programs" considers the great expansion and advancement that is coming in both *in situ* and remote sensing ocean observation platforms [e.g., unmanned surface vehicles (USVs), new advanced satellites]. In combination, they provide the potential to measure new EOVs routinely at global scale. Enhanced collaboration between the *in situ* and remote sensing communities will deliver many benefits. Efficiencies will be gained through evaluation of requirements in an integrated manner. Effectiveness will be increased through development of blended products.

In Section "Integrating Marine and Ocean Observations Into the Global Observing System" considers the opportunities provided by the World Meteorological Organization (WMO) Integrated Global Observing System (WIGOS) in fostering a more comprehensive and integrated approach across meteorology and oceanography. Enhanced collaboration between these communities will allow end users to understand observational data more completely—and be assured that observations have been quality monitored and problems identified and fixed. Easier incorporation of partner networks and expansion of observations available will enable more comprehensive products to be generated for users. The focus of WIGOS is on provision of accurate, reliable and timely weather, climate, water and related environmental observations and products. This sits well with the expanded requirements of GOOS in climate, operational services, and marine ecosystem health.

In Section "The Way Ahead" outlines the way ahead. Significant effort has been expended by the GOOS community over the last decade in setting requirements, specifying EOVs, improving observations coordination, and reinvigorating GRAs. We argue that the focus now needs to shift to ensuring the ocean observing system clearly demonstrates and is widely recognized for its fundamental role in underpinning the delivery of climate services, weather predictions, regional and global ocean assessments, fisheries management, ecosystem services, and real-time services.

THINK GLOBAL, ACT LOCAL – CHALLENGES AND OPPORTUNITIES IN COLLABORATING ACROSS GOOS REGIONAL ALLIANCES

There has been a concerted effort over the past decade to reinvigorate the GRAs in response to challenges and opportunities identified at OceanObs'09, and through development of the Framework for Ocean Observing. Several initiatives have been undertaken to increase understanding and awareness, enhance collaboration, and build capacity. While good progress has been made, much more needs to be done in the coming decade if GRAs are to realize their potential in contributing to the vision and mission of GOOS.

What Are GRAs?

GOOS Regional Alliances identify, enable, and develop sustained GOOS ocean monitoring and services to meet regional and national priorities, aligning the global goals of GOOS with the need for services and products satisfying local requirements (IOC-UNESCO, 2013). Historically, the GRAs were introduced as a way to integrate national needs into a regional system and to deliver the benefits of GOOS strategy, structure, and programs at a regional and national level. The first GRA was formed in 1994, and the most recent addition was in 2014. There are now thirteen GRAs (see **Table 1**). For more information on the function and structure of the GRAs, please see the GOOS Regional Policy (IOC-UNESCO, 2013[1]). All GRAs are focused on the provision of ocean observing information.

The leads of each GRA come together to form a GRA Council, which elects a Chair for a 2-year term, with a second term allowed. The Council can also elect a Deputy Chair to assist the Chair. A GOOS Regional Forum is held every 2 years, organized by the Chair with support from the GOOS Project Office. Between forum meetings, an action agenda is progressed through regular teleconferences. The GRA Council Chair is an *ex officio* member of the GOOS Steering Committee.

How the GRAs Are Governed

There is significant heterogeneity in the governance and funding of GRAs. Six GRAs are formed under IOC sub-commissions or related intergovernmental structures. Four are

[1] https://unesdoc.unesco.org/ark:/48223/pf0000226859

TABLE 1 | Summary of GRA governance structures (GOOS, 2018b).

GRA Name	Region	Governance structure
Black Sea GOOS	Black Sea	Memorandum of Association
EuroGOOS	Europe	International non-profit association under Belgian law, fee-based membership
GOOS Africa	African continent	Under IOC Sub-commission for Africa and adjacent Island states
GRASP	South America, Pacific Coast	Under Permanent Commission for the South Pacific (CPPS)
IMOS	Australia	Federal funding as a national research infrastructure
IOCARIBE GOOS	Caribbean	Under IOC Sub-commission for the Caribbean (IOCARIBE)
IO-GOOS	Indian Ocean	Memorandum of Association
IOOS	U.S.	Federal funding supported by legislation
MONGOOS	Mediterranean	Memorandum of Association
NEAR-GOOS	North East Asia	Under IOC Sub-commission for Western Pacific (WESTPAC)
OCEATLAN	South America, Atlantic Coast	Memorandum of Understanding
PI-GOOS	Pacific Islands	Under Pacific Islands Applied Geoscience Commission and Secretariat of the Pacific Regional Environment Programme (since 2009)
SEA-GOOS	South East Asia	Under IOC Sub-commission for Western Pacific (WESTPAC)

formed under memorandums of understanding. One is an international non-profit association, and two are funded national government programs.

Most GRAs can access funding only through *ad hoc* projects, if at all. Only U.S. Integrated Ocean Observing System (IOOS) and Integrated Marine Observing System (IMOS) have program budgets, with EuroGOOS having a member fee base.

Recent efforts across the GRAs have recognized this heterogeneity and taken a multifaceted approach to enhancing collaboration across regions, communities, and technologies. In this section we consider initiatives undertaken by the GRA Council to increase understanding and awareness, increase collaboration, and build capacity. As GOOS expands to include new observing networks (see section "The Need for New Observations and Biological and Coastal Data to Meet Expanded Requirements for GOOS") and better embrace national and multinational capabilities (see section "Harnessing the Power of National Capabilities and Multinational Collaborations"), the potential contribution of a strengthened GRA network to the GOOS vision and mission is increasingly being recognized.

Consideration will need to be given as to whether the current GRA structure is fit for this purpose.

GRA Initiatives Since OceanObs'09

Since OceanObs'09, the better resourced GRAs have taken greater responsibility for leadership within the GRA Council. U.S. IOOS was elected Chair for 2012 and 2013, and again for 2014 and 2015 with IMOS as Deputy Chair. IMOS was elected Chair for 2016 and 2017, with EuroGOOS as Deputy Chair. EuroGOOS was elected Chair for 2018 and 2019, with IO-GOOS as Deputy Chair. The intention has been to create a forum where those who are responsible for implementing regional ocean observing systems have the chance to exchange ideas, develop best practices, and work closer together.

Assessments of GRAs

An important step was the completion of self-assessments by GRAs during 2012. These assessments included basic information on governance and management, societal benefit areas being addressed, types of observation technologies being operated, and data management arrangements. The assessments were summarized and discussed at GOOS Regional Forum VI in 2013, providing a basis for identifying priorities to increase collaboration and build capacity (Fischer and Willis, 2013).

The assessments dispelled the notion that GRAs supported only the coastal component of GOOS, highlighting that several GRAs had evolved to meet a wide range of societal challenges related to both the coastal and open ocean observations. They revealed that GRAs had been active in embracing new networks (see section "The Need for New Observations and Biological and Coastal Data to Meet Expanded Requirements for GOOS"), consistent with the expanded vision and mission of GOOS. Five GRAs were operating HF radar networks, seven were operating ocean gliders, five were operating animal tagging programs, and six were operating ocean acidification (OA) networks. The assessments also highlighted the operational modeling capacities within GRAs. The information provided in the assessments has been used to advance GRA activities since 2012.

With support from the GOOS Steering Committee (via the U.S. National Aeronautics and Space Administration [NASA]), an external review and analysis of all of the detailed inputs to the GRA assessments was then undertaken (GOOS, 2015). The review report was presented at the GOOS Regional Forum VII in 2015 and included a number of actions and recommendations for the GRA Council and the GOOS Project Office (GOOS, 2017). The full report is available online (IOC-UNESCO, 2015[2]).

Mapping Ocean Observing Assets

Catalyzed by the assessment, a global inventory of ocean observing assets was established based on metadata and data supplied from GRAs. A key motivation was to encourage use of international metadata and data exchange standards across the GRAs consistent with the GOOS Regional Policy. The asset

[2]http://www.ioc-unesco.org/index.php?option=com_oe&task=viewDocumentRecord&docID=22373

map includes most platform types and most ocean regions. It is updated periodically and maintained by the European Marine Observations and Data Network (EMODNet). The number of platforms displayed on the asset map has increased three-fold between the 2015 and 2017 GOOS Regional Forum meetings.

Development of an Ocean Modeling Inventory

In order to promote a value chain approach to ocean observing, the GRAs also compiled an inventory of operational ocean modeling activities. Information on the spatial extent and parameters output (state variables) of each model was provided using an internet-based mapping tool (EuroGOOS, 2018). GRAs can update this resource as new models for their region are developed providing useful guidance to users contemplating the use of such models.

GOOS Pilot Projects

The GOOS Steering Committee has identified focused, finite lifetime development projects (GOOS pilot projects) as an effective way to drive the development of the GOOS—both for redesigning mature observing systems and for expanding the observing system into new areas. The TPOS 2020 project was an early example. Initially it appeared that GOOS pilot projects would be selected by the Steering Committee or developed through the Expert Panels. At the GOOS Regional Forum VII in 2015, it was proposed that GRAs also develop and propose GOOS pilot projects (GOOS, 2017).

The GRA Council saw this as being a particularly important development. It is impossible to identify priorities benefiting all GRAs because of their significant heterogeneity. It is much more plausible for subsets of GRAs with different levels of capability and capacity to come together around issues of common interest. GOOS pilot projects provide a mechanism to do this.

During late 2015/early 2016 the first GRA pilot project was developed. MONGOOS and GOOS Africa (with support from U.S. IOOS and EuroGOOS) developed a MEditerranean Sea-level Change And Tsunamis (MESCAT) project. Its aims were to (a) create a tide gauge network covering all coasts of the Mediterranean Sea, (b) make sea level projections and impact studies in the Mediterranean Sea, and (c) develop capacity in North African nations to operate and maintain the network. The GRA Council also identified opportunities to develop similar multi-GRA pilot projects in the Caribbean and in the Pacific Islands.

The GOOS Steering Committee approved MESCAT as a GOOS pilot project in June 2016; however, it has yet to secure funding (GOOS, 2016).

Concluding Remarks and Recommendations

Notwithstanding progress over the last decade, significant heterogeneity in the governance and funding of GRAs continues to provide challenges.

Several GRAs are founded on governance agreements that do not easily allow the addition of new partners. Stakeholder feedback suggests that GOOS needs to become more inclusive of ocean observing efforts relevant to its expanded vision and mission, and more creative in facilitating expansion and growth. This is particularly the case for biological EOVs and for continental shelf and coastal marine systems, where societal benefit is highest.

Opportunities do exist to address this challenge. Taking advantage of the GOOS Steering Committee meeting held in Colombia in June 2018, a GOOS South American Regional Workshop was organized to discuss regional projects and national strategies on marine monitoring in this region (GOOS, 2018c). The workshop was acknowledged as an historic event that gathered key players and communities from across South America who share a common interest in realizing the vision and mission of GOOS, and whose plans are thus well aligned with the decadal strategy of GOOS. It highlighted the fact that significant capability exists within the region that is not currently engaged with the GRA structures. We must understand the impediments and work to remove them.

Scarcity of funding to support multinational ocean observing efforts and genuine capacity development within nations is also serious challenge. The GRA Council has shown it is capable of developing projects to address regional priorities and develop national capacity – projects that are worthy of endorsement by the GOOS Steering Committee. However, if there are no mechanisms to fund such projects, the contribution of some GRAs toward the vision and mission of GOOS will continue to be heavily constrained.

It is hoped that the United Nations Decade of Ocean Science for Sustainable Development will provide new opportunities to address this challenge.

THE NEED FOR NEW OBSERVATIONS AND BIOLOGICAL AND COASTAL DATA TO MEET EXPANDED REQUIREMENTS FOR GOOS

Global Ocean Observing System now seeks to coordinate observations around the global ocean for three critical themes: climate, operational services, and marine ecosystem health. To address these expanded requirements, new observations and data are clearly needed. This is especially true for the measurement of biological EOVs and for extending GOOS from the open ocean into continental shelf and coastal systems.

Bringing New Observing Technologies and Networks Into GOOS

The ocean observing networks currently recognized as being part of GOOS are shown in **Figure 1** (see section "The Changing Context for GOOS – From OceanObs'09 to OceanObs'19"). There are other ocean observing networks in operation around the globe that can measure physical, biogeochemical, and biological EOVs across relevant time and space scales. GOOS needs to develop effective and efficient mechanisms to assess the readiness of new networks and facilitate their inclusion in the global system. These are not yet fully in place.

Here, the term "networks" refers to capabilities to observe the ocean and includes both collaborative frameworks of people as well as observing technologies and data management practices from national observing systems. They do not necessarily have a global design, like Argo or satellite virtual constellations. There are "global" networks where national/regional programs use common technologies to answer common questions and are coming together to share, learn, build capacity, and work to common data standards enabling interoperability where required.

As noted in Section "Think Global, Act Local – Challenges and Opportunities in Collaborating Across GOOS Regional Alliances," multiple GRAs are operating HF radar networks, ocean gliders, animal tagging programs, and OA networks. The GRA Council has advocated for formal inclusion of these networks into GOOS. The adoption of other new technologies will continue as they are developed.

High Frequency Radar

The Global High Frequency Radar Network (GHFRN) was established in 2012 as part of the Group on Earth Observations (GEO) to promote HF radar technology. At that time there was no opportunity to integrate this activity in GOOS. HF radar networks produce hourly maps of ocean surface currents within 200 kilometers of a coastline. The technology is becoming a standard component of regional ocean observing systems, and the growth of the network remains steady with approximately 400 stations currently operating and collecting real-time surface current information. However, only 2% of the world's coastline is currently measured with this technology. There are approximately 281 sites reporting to the GEO list as of 2018. Approximately 140 installations are active in the Asia-Pacific region, and this number is expected to grow with new installations in the Philippines and Vietnam. The number of organizations displaying surface current information on the GHFRN web page has also increased from seven in November 2016 to thirteen.

The GHFRN is aiming to standardize data formats across the regions, develop quality control standards and emerging applications of HF radar measurements, and accelerate the assimilation of the surface current measurements into ocean and ecosystem models. Participation in JCOMM OCG has been important in furthering these goals. The GRA Council has advocated for inclusion of HF radar as an observing element within GOOS and helped to facilitate development of a Network Specification Sheet for approval by the GOOS Steering Committee. However, this is yet to be achieved.

Ocean Gliders

Underwater ocean gliders and other autonomous surface vehicles serve as unique and versatile observation platforms. They can conduct sustained autonomous surface and subsurface ocean data collection in critical data-sparse areas that prove challenging for other observation platforms. As underwater glider operations at institutional and national levels have grown and matured, the benefits and opportunities of regional and international collaboration have been recognized.

Regionally, glider operators have come together to form user groups such as Everyone's Glider Observatory (EGO) and the Underwater Glider User Group (UG2) to share best practices, improve operational reliability and data management, and work together to improve glider monitoring, ocean observing, and development of the glider platform. Internationally, the OceanGliders group has evolved from the above groups to serve this purpose. The OceanGliders group has formed task teams to focus international glider efforts in the priority areas of boundary currents, storms, water transformation, polar regions, and data management. The GRA Council is supporting these efforts, and the OceanGliders group is engaging with JCOMM OCG as an emerging network. It is expected that ocean gliders will eventually become recognized as an observing element within GOOS given their ability to collect physical and biogeochemical measurements at a range of scales.

Animal Tracking

The GOOS Biology and Ecosystems Panel was formed during 2013. By 2018, the panel had specified nine, new biological EOVs for GOOS. These include 'fish abundance and distribution' and 'marine turtles, birds, mammal abundance and distribution.' Animal tracking technologies (both acoustic and satellite) are widely used across the globe and can provide sustained observing of species distribution and abundance.

The Ocean Tracking Network (OTN) provides a global acoustic receiver infrastructure in all of the world's five oceans[3]. With investment by the Canadian government matched through international partnerships and collaborations, OTN has deployed over 2,000 acoustic tracking stations (receivers) globally and tracks over 130 commercially, ecologically, and culturally valuable aquatic species.

Satellite tracking is being coordinated through the MEOP consortium, which stands for Marine Mammals Exploring the Oceans Pole to Pole[4]. MEOP brings together several national programs to produce a comprehensive quality-controlled database of oceanographic data obtained in polar regions from instrumented marine mammals. Over 500,000 vertical profiles of temperature and salinity have been collected since 2004 in the world ocean by attaching tags on marine mammals, such as Southern elephant seals. These data are complementary to those collected by Argo and it has been demonstrated that assimilating the temperature profiles into a global ocean forecast model has a positive impact in the predicted temperature and salinity in seal-sampled areas where other observational data are sparse (Carse et al., 2015).

Several GRAs, including U.S. IOOS, EuroGOOS, and IMOS, operate animal tracking programs and are working to support international animal tracking data standardization. The community is now engaged with JCOMM OCG as an emerging network under the title of 'Animal-borne instrumentation.'

[3] http://oceantrackingnetwork.org/

[4] http://www.meop.net/

Global Ocean Acidification Observing Network (GOA-ON)

The GOA-ON[5] is a collaborative international approach to document the status and progress of OA in open-ocean, coastal, and estuarine environments, to understand the drivers and impacts of OA on marine ecosystems, and to provide spatially and temporally resolved biogeochemical data necessary to optimize modeling for OA.

GOOS Regional Alliances with OA programs focus their OA activities through GOA-ON and the GOA-ON Data Explorer. The data explorer provides access and visualization to ocean acidification data and data synthesis products being collected around the world from a wide range of sources, including moorings, research cruises, and fixed time-series stations.

Global Ocean Acidification Observing Network attended the GOOS Regional Forum VIII in 2017 (GOOS, 2017). It is developing "GRA-like" regional networks, including OA-Africa, North American hub, Pacific Island hub, Arctic hub, WESTPAC, and Australia. Furthermore GOA-ON adheres to GOOS data principles, and the global data portal is built on the foundation of the U.S. IOOS data portal. Opportunities were identified for GRAs to assist GOA-ON in building its regional networks, and for GOA-ON to assist GRAs in bringing non-traditional partners into the GOOS enterprise.

Other Networks

Several other initiatives are underway to address gaps in global observing capability, and to find efficiencies in and opportunities for the integration of sustained biological observations. These include the GEO' Marine Biodiversity Observation Network (MBON). MBON is prioritizing observations of marine life to address specific user needs, identifying and integrating those observations where feasible, addressing data management challenges to ensure broad accessibility of these data, and developing products that overlay biological observations with physical and biogeochemical observations to describe impact of ecosystem change on living communities. MBON funded partners and collaborators are actively supporting development of specification sheets and implementation plans for the full complement of GOOS Biology and Ecosystem variables.

Other cost-effective instruments have been developed and used in coastal ocean monitoring, e.g., FerryBox systems and shallow water Argo profiles (with oxygen and Chl-a measurements). For the purpose of environment assessment, a significant amount of chemical and biological observations are made in coastal waters and delivered offline, mostly not shared with the operational oceanography community. Further optimization of existing coastal observational networks and integration between different monitoring communities is needed.

Global agreement on EOVs has the additional benefit of providing a clear focus for existing networks to come together and integrate their methods and approaches to achieve a common goal. One example is the move toward "Globally consistent quantitative observations of planktonic ecosystems" being advocated by the Lombard and Boss et al Community White Paper. Observations of planktonic ecosystems are currently undertaken through discrete water samples, net tows, continuous plankton recorders (CPR), and satellite ocean color. Historically there has been limited integration across these methods. An EOV focus provides the opportunity to extract much greater value from the combination of these methods, particularly when coupled with biogeochemical and ecosystem modeling approaches.

Observations Coordination, and Data Assembly and Exchange

It is encouraging to see that JCOMM OCG has identified HF radar, ocean gliders and animal-borne instrumentation as emerging networks. These networks aspire to a global mission, and JCOMM OCG can provide advice and rigor in developing the policies, processes, and systems required to achieve this.

There will, however, be a limit to the scope of JOCMM OCG activities, which presently covers networks that measure physical and bio-geochemical EOVs. For example, the GOOS Biology and Ecosystems Panel has specified new biological EOVs covering hard corals, seagrasses, macroalgae, and mangroves. It is difficult to see how observations coordination for the global networks required to measure these EOVs could be done more effectively through JCOMM OCG.

Additional, complementary observations coordination mechanisms will be required, though care needs to be taken in avoiding network-specific approaches that fail to realize the benefits of an integrated, biophysical observing system. A clear focus on outcomes and societal benefit will be the key. To use but one example, measuring hard coral cover as an EOV will be enormously valuable. Providing the tools to monitor and manage coral bleaching, however, will require the integration of satellite sea surface temperature (SST) and *in situ* sampling technologies, as well as numerical modeling and forecasting.

Related to the above, new observing technologies and networks aspiring to become part of GOOS must develop robust and sustainable mechanisms for data assembly and exchange. It is significant that the HF radar, ocean gliders, and animal-borne instrumentation 'emerging networks' are all working on data standardization within their communities. This should be strongly encouraged and supported.

The JCOMM Open Access Global Telecommunication System (GTS) pilot project is an exciting development that has potential to greatly enhance oceanographic data assembly and exchange. On one hand, the rigor and robustness of the WMO GTS sets a standard for which the oceanographic community can aim. On the other hand, many in the oceanographic community currently find it difficult to get data into and out of the GTS, limiting its broader utility. The Open Access GTS pilot project aims to retrieve newly inserted data from the GTS, decode it from the WMO Binary Universal Form for the Representation of meteorological data (BUFR) format, add the data and metadata to a database, and provide access via web-accessible tools and visualizations.

[5] http://goa-on.org/

Expansion of GOOS to encompass biological EOVs and continental shelf and coastal marine systems presents some distinctive challenges in terms of data access, assembly, and exchange. The Ocean Biogeographic Information System (OBIS) is working with the GOOS Biology and Ecosystems Panel on these challenges. OBIS aims to provide a global, open-access data and information clearinghouse on marine biodiversity for science, conservation, and sustainable development.

Concluding Remarks and Recommendations

In the next decade, inclusion of more physical-biogeochemical observing systems such as HF radar, ocean gliders, animal tagging and tracking, Ferry Box and shallow water profiling Argo floats should be considered and realized as observing elements within GOOS. Better coordination among various systems, such as the GOA-ON and MBON should be facilitated by GOOS. Observations coordination and data assembly/exchange will be essential to realizing the opportunities provided by new collaborations across regions, communities, and technologies.

HARNESSING THE POWER OF NATIONAL CAPABILITIES AND MULTINATIONAL COLLABORATIONS

Most investment in global ocean observing comes through nation-states. This manifests through cooperative investment by multiple nations in international programs and through investment in national programs with broader reach. International programs such as Argo and satellite virtual constellations have traditionally been the focus of GOOS. Here we focus on investments in national programs with broader reach, to better harness the power of national capabilities and multilateral collaborations.

Consideration is given to national programs already engaged as GRAs, in the United States, Australia, and Europe. In other cases, investments are being made into national programs that are not currently aligned with GRAs in India, South Africa, Canada, and South America. In addition, recent multinational projects such as the TPOS 2020 and AtlantOS are stimulating discussion about governance of basin-wide ocean observing systems into the future.

National Capabilities and Regional Alliances

Since OceanObs'09, the GRA Council and GOOS Steering Committee have increasingly recognized the value of engaging with strong national programs that meet the requirements of the GOOS Regional Policy (IOC-UNESCO, 2013).

Current GRAs

As Chair of the GRA Council from 2012 to 15, the leadership demonstrated by U.S. IOOS has been crucial in reinvigoration of the GRAs. U.S. IOOS has partnered with nations in adjacent waters, invested in new technologies and networks (and supported them in contributing to a global mission), and embraced international data standardization. It has shown how a national program can operate as a regional alliance to support the vision and mission of GOOS.

Australia's Integrated Marine Observing System (IMOS) is the newest GRA. IMOS was established in 2007 and has benefited greatly from the thinking that emerged from OceanObs'09 and through development of the Framework for Ocean Observing. IMOS was recognized as a GRA in 2014.

EuroGOOS is the European component of GOOS. It brings together 42 member-institutions and five regional ocean observing systems within Europe. EuroGOOS works closely with MONGOOS (in the Mediterranean) and Black Sea GOOS. A community-driven coordinating framework for Europe's ocean observing capacity is currently under development. The European Ocean Observing System (EOOS) will link the disparate components of the ocean observing system and promote shared strategies, infrastructure development, data standardization, open access, and capacity building.

Opportunities to Strengthen the GRAs

As noted in Section "Think Global, Act Local – Challenges and Opportunities in Collaborating Across GOOS Regional Alliances," the GRAs are not homogeneous in their makeup. In some cases, mature ocean observing networks exist within IOC member countries that are not yet part of the GOOS enterprise.

India

India plays a major role in IO-GOOS, a GRA focused at basin scale in the Indian Ocean. India, however, also has a very mature national Ocean Observing Network (OON), operating Argo floats, XBTs, current meters, wave rider buoys, tsunami buoys, tide gauges, ship-based weather stations, and a mooring network. The collective ocean observing capability of the Indian National Centre for Ocean Information Services (INCOIS), National Institute of Ocean Technology (NIOT), Earth System Science Organization (ESSO), and related organizations is globally significant. A presentation on India's OON was delivered at the GOOS Regional Forum VIII in 2017, and IO- GOOS is now Deputy Chair of the GRA Council. These are small but hopefully significant steps in better engaging India's national capability in the GOOS enterprise.

South Africa

Global Ocean Observing System Africa is a GRA that has a massive amount of ocean to observe, yet it is currently unfunded. Considering the oceans around the African continent at regional level, so as to take advantage of national strengths, may be one way to move forward. The South African Environmental Observation Network (SAEON) covers both terrestrial and marine environments. It includes a marine-offshore systems (Egagasini) node and a coastal (Elwandle) node. The Sentinel coastal site for long-term ecological research consists of 100 *in situ* instruments collecting data (mostly delayed mode) continuously since 2008. Including SAEON as a GRA would encourage government support, technical support from other

GRAs, setting of requirements and standards, support for the measurement of EOVs, and access to calibration facilities.

North America

Within North America, only U.S. IOOS is formally part of the GRA Council. Canada has significant capability in ocean observing, through programs such as the OTN, Ocean Networks Canada (ONC) and MEOPAR. Canada has embarked on a process to establish a Canadian IOOS, and they are planning to cooperate with U.S. IOOS as part of a larger North America GRA.

Mexico currently does not have a government-wide ocean observing system but has been developing its ocean observing capacity through the Consortium of Institutions for Marine Research (CIIMAR). CIIMAR and the U.S. IOOS's Gulf of Mexico Regional Association have signed a memorandum of understanding and exchange expertise in data management.

South America

In South America there are three GRAs, which represent joint efforts of countries and institutions to integrate national needs into regional systems. The GRAs aim to develop and implement operational ocean monitoring systems based on data sharing and enhancing capacity development. In this region, representation on the GRA Council has generally been through naval institutions. There are, however, several mature programs/projects operating in South America at the subnational, national, or regional level that could strengthen and expand the ocean observing capabilities in the region and be integrated into GOOS. The recent GOOS South American Regional Workshop (see section "Concluding Remarks and Recommendations") recommended that regional IOC structures (the GRAs) be revitalized to incorporate a larger multidisciplinary observing community and to improve their communication to all stakeholders, capitalizing on opportunities (Miloslavich et al., 2018).

Two of the thirteen GRAs operate in the East Asian Region i.e., NEAR GOOS and SEAGOOS. Both operate under the auspices of the IOC Sub-Commission for Western Pacific (WESTPAC). Given the dynamic nature of ocean-based economic development in this region, and the importance of ocean observing to inform this development, opportunities are arising to significantly increase the role of East Asian countries in the GOOS enterprise. The TPOS 2020 project provides one example. The involvement of China, as well as South Korea, is emerging as fundamental to successful implementation of the TPOS 2020 vision.

Alliances of the Future

AtlantOS

In May 2013, the European Union (EU), Canada, and the United States signed the Galway Statement on the Atlantic Ocean Cooperation, with the stated goal of "advancing a shared vision on an Atlantic Ocean that is healthy, resilient, safe, productive, understood and treasured so as to promote the well-being, prosperity, and security of present and future generations" (Geoghegan-Quinn et al., 2013). AtlantOS has the goal of transitioning a loosely coordinated set of existing ocean-observing activities into a fit-for-purpose Integrated Atlantic Ocean Observing System (IAOOS). AtlantOS will conclude in 2019, and while there have been good discussions on a design and framework of an IAOOS, a funded, sustained system is not a result of this effort. There has been a concern that AtlantOS was too focused on the North Atlantic, which resulted in the Belem Statement being signed in July 2017 to strengthen the successful partnership with the European Commission and the Department of Science and Technology of Brazil and South Africa (Moedas et al., 2017). While this agreement has not directly resulted in a funded project, it has set up another convening forum to discuss issues in the southern Atlantic.

TPOS 2020

The TPOS 2020 Project will evaluate, and where necessary change, all elements that contribute to the current configuration of TPOS based on a modern understanding of tropical Pacific science (Legler and Hill, 2014). It is a focused, finite term project established in 2014 in response to deterioration of the tropical moored buoy array in the Pacific in 2012–2014. While TPOS 2020 provides an opportunity to evaluate new technologies to enhance and redesign the observing system in this important region, its ongoing governance is yet to be worked out. A TPOS Resources Forum has been established to consider the issues of long-term funding and governance.

The Southern Ocean Observing System (SOOS)

Southern Ocean Observing System is an international initiative of the Scientific Committee on Antarctic Research and the Scientific Committee on Oceanic Research (SCOR) (Rintoul et al., 2010). SOOS was officially launched in 2011. In the Antarctic region, scientific activities are guided by international treaties and organizations outside the IOC system. Furthermore, the SOOS project office has limited funding and needs to focus its efforts on the highest priorities. For these reasons, SOOS participation in the GRA Council has not yet been realized.

Group on Earth Observation

The GEO is an intergovernmental organization working to improve the availability, access and use of earth observations. GEO is structured with Flagships, Initiatives, Community activities, and foundational tasks. There are two efforts within GEO where the ocean community participates. First, as part of the GEO Biodiversity Network (GEOBON), the United States funding of MBON projects introduced a marine component to the GEOBON. MBON is working on a pole-to-pole effort under the AmeriGEO regional effort of GEO. Through GEO's Blue Planet initiative, the ocean community representing the observing, data management and modeling community come together to advance and exploit synergies among the many observational programs devoted to ocean and coastal waters and, in particular, raise awareness of the societal benefits of ocean observations at the public and policy levels. For Blue Planet, the United States has resourced an Executive Secretariat and Australia funds the website. Support is also received from POGO and the European Union. The initiative is organized through six working groups, two projects consisting of (1) an early warning system for reef-lined islands and (2) a multi-hazard information and alert system for the wider Caribbean, and two nodes – MBON and water quality.

Concluding Remarks and Recommendations

There are several issues to consider if we are to harness fully the power of national capabilities and multinational collaborations within the GOOS. The benefits of being part of GOOS need to be much more apparent to countries, institutions, and programs. GOOS needs to become more inclusive, with effective and efficient mechanisms to facilitate new partners and partnerships.

Global Ocean Observing System is part of the United Nations system with representation from individual countries. The GEO is an intergovernmental voluntary organization that operates through member nations and participating organizations with a focus of the use of earth observations (air, land, and sea) within the policy arena. What both organizations share is the fact that implementation is based on national contributions and efforts. They are both convening bodies, and alignment with them can help bolster national efforts. Further, neither GOOS nor GEO are funding bodies in their own right, but nations, and in particular the European Union, use both of these organizations as mandates for their annual funding calls. GEO has evolved to align its work program through flagships, initiatives, community activities, and foundational tasks, all of which are articulated through plans that span 2 years. It is recommended that an implementation planning approach be adopted by GOOS in moving forward, providing clearer pathways for engagement.

While GOOS has evolved within the last 10 years and has begun to have a more inclusive focus, partnering is an area in which there must be continued focus. In advocating for emerging networks 600 and pilot projects, the GRA Council found that GOOS processes were either unclear or did not yet exist. GOOS should continue to strongly endorse new partners and partnerships, which will in turn help the national efforts to sustain funding.

The challenge of sustained funding must be addressed, where sustained funding is sometimes equated with transition from research to operational systems. In reality, there are few examples of research to operational transitions resulting in sustained funding. Here we suggest an alternative nomenclature of sustained and experimental observations, providing an overall roadmap that connects the various observing efforts, along with a community-wide consistent message on the importance of ocean observing.

U.S. IOOS has long-term funding within the U.S. government and is considered an operational ocean observing system that supports research. The U.S. contribution to Argo is within the research arm of the National Oceanic and Atmospheric Administration (NOAA) and has long-term funding in support of operational forecasting. Within Australia, IMOS was established as a research infrastructure, but through long-term funding and open data access, it has been able to support both research and operational needs. Within Europe there has been a recognition that, while ocean observing data and information are required to meet many societal challenges—from food security, to climate change, ecosystem health, or water management—the European *in situ* ocean observing capacity is still fragmented and broadly not sustained. While the space-borne ocean observations are funded through the Copernicus program, most in situ observations are supported through short-term projects, with no guarantee of a long-term sustainability. Europe has embarked on establishing the EOOS in order to address this dichotomy.

Recommendations:

(1) Resources are finite and the community cannot be balkanized. A robust dialogue is encouraged on how GOOS wants to organize the contributions by its members. Specifically, while the GRAs have shown progress, challenges remain. There has been the emergence of basin scale efforts. How can these two structures be complementary? Is there a hybrid organization that should emerge?
(2) The GOOS Regional Council has been active in the last 10 years but has never been endorsed by the IOC. Pending the discussion on the overall organization, the recognition by IOC of the GOOS Regional Council can help strengthen the foundation of the GRAs.
(3) GOOS should assess and develop a prospectus on the benefits of participating within a GRA to entice increased membership by national programs.
(4) GOOS should adopt a more inclusive approach to new networks and be a welcoming system to emerging technologies. Clear criteria and processes for inclusion should be written and adopted.
(5) GOOS and GEO are both convening authorities that by themselves do not have resources for the implementation of the observing systems. GOOS and GEO do appeal to different leaders and funding sources. These organizations should find ways to support each other and remove perception that these are competing efforts.
(6) GOOS should find new ways to work with GEO to make the compelling case that ocean observations are critical to policies and economic prosperity.
(7) GEO's new Secretariat Director has stated that GEO should take the lead in providing curated in situ observations; GOOS should lead the effort for ocean observations.
(8) It is recommended that GOOS adopt the following nomenclature to help advance discussion of sustained funding:

- Sustained observations: measurements taken routinely that are committed to monitoring on an ongoing basis. These measurements can be for public services or for Earth-system research in the public interest.
- Experimental observations: measurements (taken for a limited observing period) that are committed to monitoring for research and development purposes. These measurements serve to advance human knowledge, explore technical innovation, improve services, and in many cases, may be first-of-their-kind.

In this way nations could continue to seek different types of funding sources as appropriate and be recognized as observations that need to be sustained over a long period. This can also be helpful in communicating a consistent message to prospective funding agencies.

GOOS AS A MECHANISM FOR PARTNERSHIP BETWEEN GLOBAL SATELLITE AND *IN SITU* PROGRAMS

In the past decade, ocean observations have made great strides in expanding EOVs from *in situ*, satellite and other remote sensing platforms, as well as in improving accuracy and spatial-temporal resolutions and coverage. In part, the ocean observing system design, implementation, and product generation are guided by the integration of satellite and *in situ* observations for maximizing benefits and minimizing costs. This section reviews the progress made in those areas and envisions future improvements in anticipation of new capabilities.

Satellite Oceanographic Observations and Product Development and Services

Earth-observing satellites have been operated by individual countries for their national needs and 663 priorities. International collaborations have also been forged, driven by both scientific/application 664 needs and cost constraints. The constellation of satellites launched jointly and/or separately by different countries have recently shown added value to resolve finer and shorter time scale variability of the ocean and atmosphere when data from multiple satellites flying concurrently are merged together. This highlights the importance of international coordination to ensure the continuation of the constellation of Earth-observing satellites, and the consistent quality control and timely open access of the data. As an example, the operational polar-orbiting satellites operated by several countries are sketched in **Figure 3** for two decades spanning the OceanObs'19. Here the data are mined from the WMO Observing System Capability Analysis and Review Tool [OSCAR], discussed in Section "Data Exchange Under WIGOS," as of Oct 15, 2018[6].

As the satellite technology advances, more advanced sensors for more essential ocean and atmospheric variables are added. For example, the new NOAA Joint Polar Satellite System (that includes the EUMETSAT Metop) satellites are equipped with advanced sensors and include: (1) the Advanced Technology Microwave Sounder (ATMS, for measuring moisture and temperature); (2) the Cross-track Infrared Sounder (CrIS, for monitoring moisture and pressure); (3) the Ozone Mapping and Profiler Suite (OMPS, for measuring ozone levels; (4) the Visible Infrared Imaging Radiometer Suite (VIIRS, for observing weather, climate, oceans, nightlight, wildfires, ice movement, and changes in vegetation and landforms); and (5) the Clouds and the Earth's Radiant Energy System (CERES).

In addition to the world's operational weather and ocean satellites, some space agencies also operate research-oriented, Earth-observing satellites. For example, NASA (U.S.) has been running various research Earth Observing System (EOS) satellites since the 1980s. Many of these satellites are joint missions with NOAA and other international partners like European Space Agency (ESA), such as the Jason altimeter satellites. These satellites measure essential climate and Earth environmental variables such as radiation, clouds, water vapor, and precipitation, the oceans states, greenhouse gases, land-surface hydrology and ecosystem processes, glaciers, sea ice, and ice sheets, ozone and stratospheric chemistry, and natural and anthropogenic aerosols[7]. Some near-future missions include the Surface Water Ocean Topography mission to make a global survey of Earth's surface water, giving scientists the first comprehensive view of Earth's freshwater bodies from space and much more detailed measurements of the ocean surface than ever before.

Complementary to polar-orbiting satellites, Geostationary Operational Environmental Satellites (GOES) provide more continuous monitoring of the Earth's environment, ensuring a constant surveillance for severe weather conditions (e.g., tornadoes, flash-floods, hail storms, and hurricanes). Started in 1975, the latest U.S. GOES generation is the GOES-R series with more advanced sensors on four satellites planned: GOES-R/GOES-16 launched in 2016; GOES-S/GOES-17 launched in 2017; GOES-T planned for 2020; and GOES-U planned for 2024. In addition EUMETSAT operates the Meteosat satellites: Meteosat-8, -9, -10 and -11 that operate over Europe, Africa and the Indian Ocean.

In Europe, a systematically coordinated Earth-observing and monitoring program called Copernicus is managed by the European Commission and consists of two major components: the space component performed by the European Space Agency (ESA), and the *in situ* component performed by the European Environment Agency and EU countries. The space component consists of two groups of satellites: the Copernicus dedicated satellites (the six "Sentinels Satellites") and the Contributing Missions, roughly thirty satellite missions that are operated by national, European, or international organizations. EUMETSAT is responsible for operating the Sentinel-3 satellites, with ESA support, and delivering the marine data and will also operate and deliver products from the Sentinel-4, and Sentinel-5 instruments, and the Sentinel-6 satellites.

In Asia, the Japan Aerospace Exploration Agency (JAXA) manages the Japanese Earth Observation Satellites, including the current Global Change Observation Mission-Climate/Water (GCOM-C, GCOM-W), the Global Satellite Mapping of Precipitation (GSMaP), and AMSR-E. The Indian Space Research Organization operates Indian's Earth Observation Satellites, include OceanSat-1/2 and SCATSAT (provide wind vector data products for weather forecasting, cyclone detection and tracking services to the users), INSAT-3D/3DR, the Satellite with ARGOS and ALTIKA (SARAL, a joint Indo-French satellite mission for ocean surface altimetry measurements). In China, the Chinese Meteorological Agency (CMA) operates the weather satellites, the Fengyun series, and the Chinese State Oceanic Administration (SOA) operates oceanographic satellites, the Haiyang series. In

[6]https://www.wmo-sat.info/oscar/satellites

[7]https://eospso.nasa.gov/mission-category/3

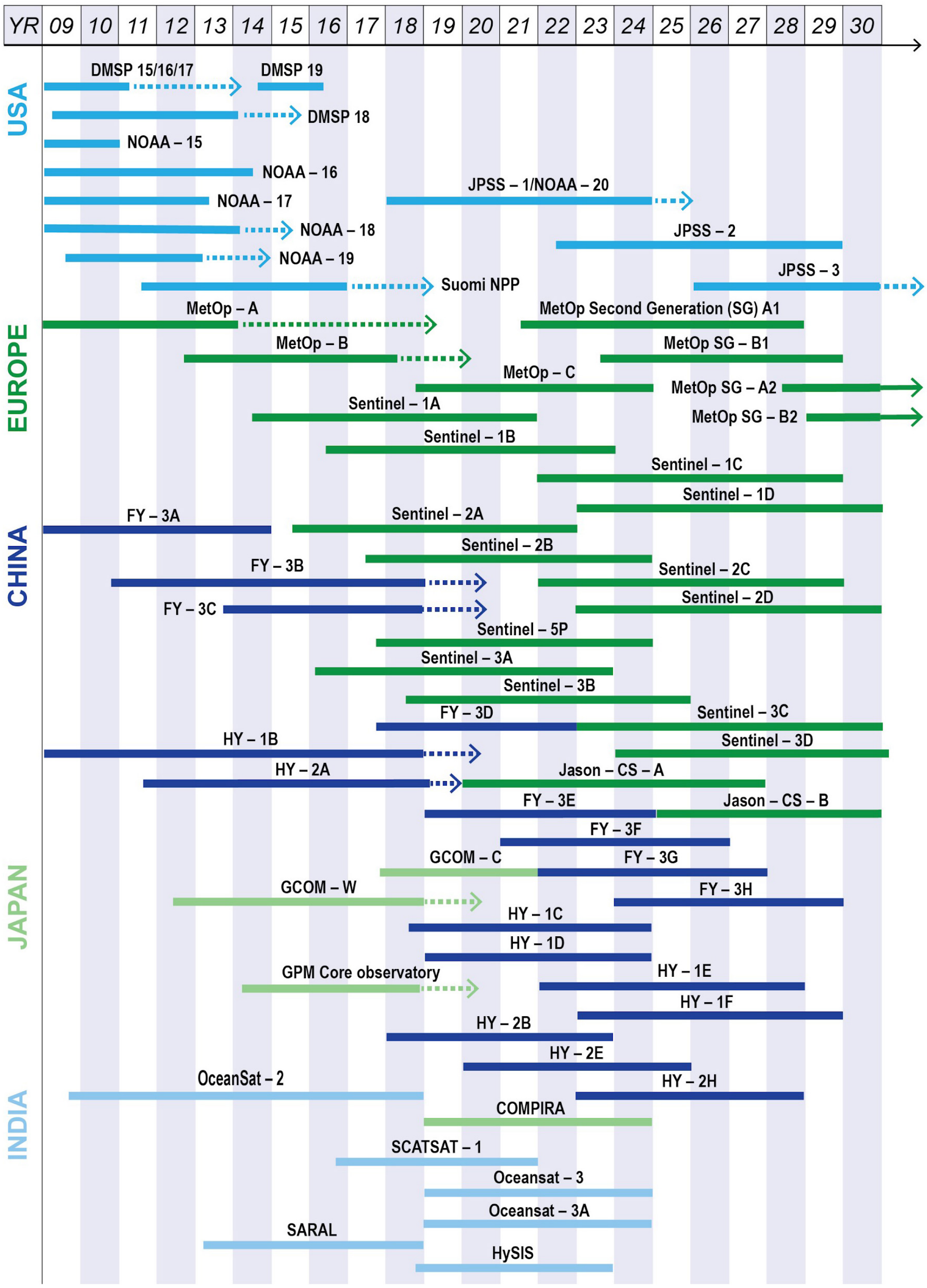


FIGURE 3 | A schematic sketch of major operational polar-orbiting satellites, showing the wealth of data from which blended products can be generated in response to increased needs on spatial-temporal resolutions and accuracy for research and societal applications.

2018, China-France Oceanography Satellite (CFOSAT) will be launched to study ocean surface winds and waves.

In situ Oceanographic Observations and Product Development and Service

In addition to coordinated regional observing systems such as the GRAs discussed earlier, internationally, the WMO/IOC JCOMM serves as a focal point for coordinating worldwide *in situ* observations and data management. A snapshot of the worldwide observing system monitored by the JCOMM in situ Observations Programme Support Centre (JCOMMOPS) is shown in **Figure 4**.

Major ocean surface observing platforms include ships, moored and drifting buoys, Argo floats, and gliders. Their data are used for ocean and weather forecasts, climate research, and monitoring/societal applications. Data from many of

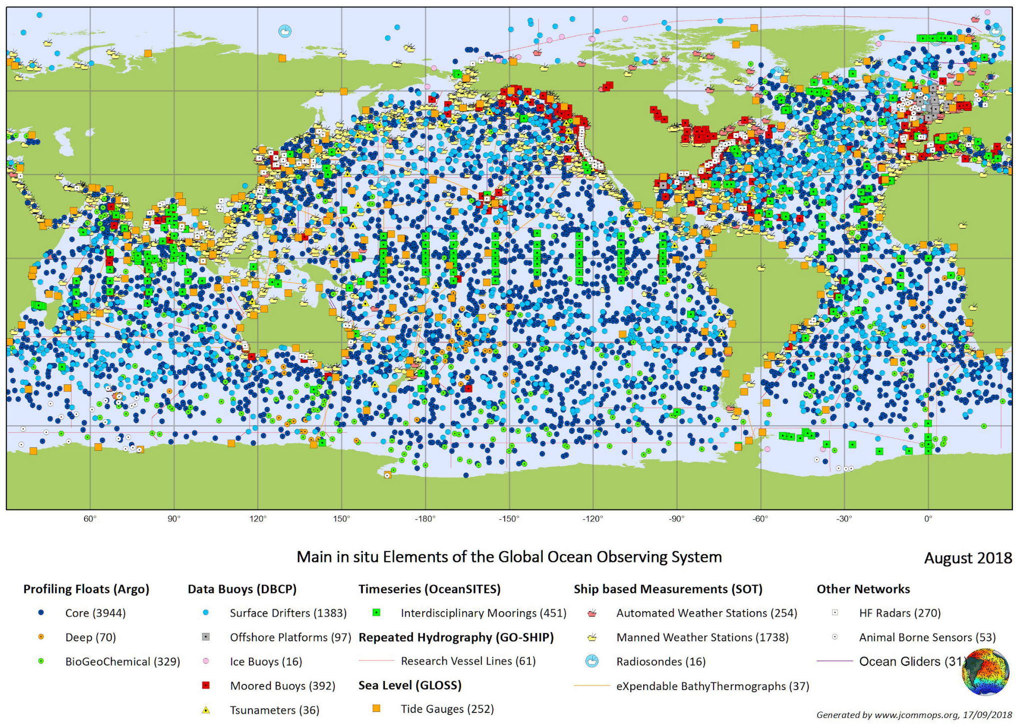


FIGURE 4 | A snapshot of global ocean observations generated by JCOMMOPS (JCOMM, 2018).

these observing systems, such as the moored buoys from the TAO/TRITON, RAMA, PIRATA, OceanSITES, various national and coastal buoy networks, ship data from SOOP/VOS/VOSclim, and Argo, are also reported in near-real-time to operational forecast centers via the WMO GTS.

Ships have the longest history of observations, starting in 1662 and collected in the International Comprehensive Ocean-Atmosphere Data Set (Freeman et al., 2017). Surface drifting buoys became abundant in the late 1970s (Freeman et al., 2017) and sustained with a global requirement (Zhang et al., 2009). Argo floats became abundant in the 1990s delivering measurements of temperature and salinity made during vertical profiles together with measurements along the floats subsurface drift trajectories. Although Argo floats originally focused on temperature and salinity, inclusion of other parameters, such as biogeochemical variables, had been called for and coordinated at the OceanObs'09 (Claustre et al., 2009; Gruber et al., 2010). Biogeochemical (BGC)-Argo floats with additional sensors for oxygen, pH, nitrate, chlorophyll, backscatter, and irradiance have been increasing since then with international participations[8]. The Southern Ocean Carbon and Climate Observations and Monitoring project has demonstrated successful application of BGC-Argo floats at a basin-scale and has been responsible for much of the recent expansion of biogeochemical profile data. As of October 8, 2018, there are 10,413 O_2 profiles obtained by 313 sensors/floats, 3,692 NO_3 profiles by 135 sensors, 2,481 pH profiles by 104 sensors, 7,244 Chl-*a* and suspended particles by 209 sensors, and 2,949 downwelling irradiance profiles by 60 sensors.

New technologies and unmanned surface vehicles (USVs) are being integrated into ocean observing systems. Among the most recent additions to the GTS are data from the Saildrone USV. The NOAA- Saildrone partnership has conducted four missions in the Arctic region, two missions for the Tropical Pacific Observing System (TPOS), one fisheries survey mission on the west coast of North America, and test missions in the Southern Ocean. The Saildrone platform is a truly integrated system, equipped with a suite of sensors measuring meteorological, oceanographic, physical, and biogeochemical variables. In addition, a number of commercially available USVs have been developed and these are increasingly being used by the research community and industry, e.g. the Wave Glider, AutoNaut and Sailbuoy, and are all capable of carrying meteorological and oceanographic sensors and contributing to GOOS.

Community and International Collaborations

As Earth's climate and environmental conditions are without national boundaries, international coordination is intrinsically needed to be successful. In fact, at the very beginning of the U.S. weather satellite missions, Dr. Harry Wexler, the key person in developing the TIROS satellites, had proposed and promoted the idea of a World Weather Watch (WWW) from 1959, and served as the lead negotiator for the U.S. in talks with the U.S.S.R. concerning the joint use of

[8]http://biogeochemical-argo.org

meteorological satellites. Now, under the Committee on Earth Observation Satellites (CEOS, established in 1984), the current 60 participating agencies operate 156 satellites including ocean observing satellites. CEOS is the mechanism that brings these organizations together to collaborate on missions, data systems, and global initiatives that benefit society as a whole, while aligning with their own national and agency missions and priorities. On the *in situ* observations, the WMO/IOC JCOMM is a key organization in coordinating international marine observations. Closer collaboration between CEOS, JCOMM and GOOS needs to be forged.

Blended Satellite and *in situ* Products and Services

Application needs for ocean and weather forecasts, scientific research and assessments, and societal applications require increasingly higher spatio-temporal resolution, accuracy and coverage. However, observations by each individual system have limitations, thus products generated by blending multi-resource observations have been needed and produced. Product resolutions are constrained by available observational data, as shown in the sampling study of Zhang et al. (2006) for multi-satellite blended sea winds (Zhang et al., 2006). Also, bias correction is a key step in generating blended products: as a case for integrating satellite and *in situ* ocean observations for SST, Zhang et al. (2009) simulated required *in situ* data density to reduce satellite SST biases to a sufficiently small level (Zhang et al., 2009).

Bias corrections are needed not only between satellite and *in situ* observations (Reynolds et al., 2002) but also between *in situ* observations themselves (Smith et al., 2008; Huang et al., 2017; Huang et al. (2018) or between satellite observations themselves (Yang et al., 2016). In Huang et al. (2017), a systematic ship-buoy SST offset of about 0.12°C was found and corrected before merging the ship-buoy SSTs into a gridded dataset. Similarly, a systematic Argo float SST and buoy SST offset of about −0.03°C was found and corrected, and in Huang et al. (2018), the relative roles of Argo floats and moored/surface drifting buoys are analyzed.

Various groups have established databases for quality monitoring of *in situ* and satellite data and blended products [e.g., NOAA's *in situ* SST quality monitor (*i*Quam); Xu and Ignatov, 2014 and SST quality monitor (sQuam; Dash et al., 2010)]. The Group for High Resolution Sea Surface Temperature (GHRSST) is an open international science group that promotes the application of satellites for monitoring sea surface temperature (SST) by enabling SST data producers, users and scientists to collaborate within an agreed framework of best practice. GHRSST provides a framework for SST data sharing, best practices for data processing and a forum for scientific dialogue. Data from multiple sources are used to generate the GHRSST Multi-product Ensemble (GMPE) SST analysis (Martin et al., 2012). POES and GOES blended SSTs are produced at NOAA (Maturi, 2010).

National oceanic and atmospheric administration's Coast Watch and Ocean Watch program collects and serves satellite observational data (sea surface temperature, sea surface height, sea surface salinity, sea surface winds, and sea surface ocean color), together with *in situ* data quality monitoring.

For biogeochemical variables, Amin et al. (2015) assessed GOES satellite-based ocean color products using *in situ* networks (Amin et al., 2015). Land et al. (2018) used a database of satellite in situ matchups to generate a statistical model of satellite uncertainty as a function of its contributing variables for ocean color chlorophyll-*a* and showed that most errors are correctable biases (Land et al., 2018). Martínez-Vicente et al. (2017) examined the differences among phytoplankton carbon (*Cphy*) estimations from six satellite ocean color algorithms by comparison with *in situ* estimates, and large (>100%) biases have been found (Martínez-Vicente et al., 2017). Under the European's Copernicus Ocean Colour Climate Change Initiative (OC-CCL), chlorophyll product was compared to the Copernicus Marine Environment Monitoring Service products and GlobColour reanalysis products. Ocean carbon examples include the validation of NASA Orbiting Carbon Observatory satellite data by *in situ*, moored CO_2 observations (Chatterjee et al., 2017) and creation of surface seawater pCO_2 and CO_2 flux maps from observation-based algorithms applied to satellite SST and color (Feely et al., 2006; Landschützer et al., 2016).

Concluding Remarks and Recommendations

Looking to the next decade, we foresee great expansion and advancement in both *in situ* and remote sensing ocean observation platforms, with the expansion of EOVs (e.g., biogeochemical variables observed routinely). Blended products can be improved through consideration of the new and improved satellite and *in situ* systems. This whitepaper invites the *in situ* and remote sensing observation communities to work more closely to suggest approaches for improvements of the ocean observing system and EOV products through an integrated, multi-platform perspective. Specifically:

Recommendation: GOOS should serve as an agent to strengthen the ties between oceanographic space and *in situ* observation systems to maximize benefits and minimize cost.

Recommendation: In coordination with WMO/IOC JCOMM, CEOS and others, GOOS should pay particular attention to development and improvement of EOV-based products that integrate across various ocean-observing systems. Additional needs include historically consistent data records for monitoring and assessing environmental changes, and extending physical climate data records to biogeochemical and ecosystem variables.

INTEGRATING MARINE AND OCEAN OBSERVATIONS INTO THE GLOBAL OBSERVING SYSTEM

As noted earlier in this paper, GOOS collects essential data for monitoring and improving understanding of our oceans and climate to provide operational services (prediction of ocean-related hazards such as tsunamis, storm surges, and high waves) and in the last decade has expanded into marine ecosystem services. In particular GOOS data are essential for weather forecasts that are critical for the safety of life at sea (severe weather and waves) and coastal protection (storm surges and wave overtopping), and climate change services that support adaptation and mitigation policies. WMO is one of the sponsors of GOOS, and its members, through many of their National Meteorological and Hydrological Services (NMHS), provide observations for GOOS (primarily from ships and buoys) and are users of GOOS data. Virtually all products and services generated by NMHS rely on data from across various domains: land, sea, and air, whether measured *in situ* or remotely sensed (e.g., from space). This has led to the WMO Global Observing System (GOS) of the WWW Programme, which has over the years developed in an incremental way and is now evolving into the WIGOS.

WIGOS – The WMO Integrated Global Observing System

In 2013 the Implementation Plan for the Evolution of Global Observing Systems (EGOS-IP) was published. EGOS-IP set out the plan for developing the WMO Global Observing Systems covering the period 2012–2025 and their role within the collective WMO Integrated Global Observing System (WIGOS) "system of systems" (WMO, 2013). WIGOS provides a framework for all the WMO-sponsored and co-sponsored observing systems, encompassing both *in situ* and remotely sensed observations—within which GOOS is an important component. The implementation of WIGOS is one of seven strategic priorities of the WMO and aims to foster the evolution of its observing systems, many of which have evolved independently, into a more comprehensive and integrated system. This will provide a more consistent system for the delivery of weather, climate, water, and related environmental observations and products generated by WMO members and programs and make major contributions to the Global Earth Observation System of Systems (GEOSS). Further information on WIGOS is available in the *Guide to WIGOS* (WMO, 2017). However, it is important to recognize that WIGOS is about much more than simply integrating observing networks, as it includes system/network design, planning and evolution; system operation and maintenance; data quality monitoring and management; standardization, interoperability and data compatibility; discovery and availability of data and metadata; capacity development; communications and outreach – all of which are appropriate to GOOS.

The component observing systems of WIGOS are: (a) the GOS of the WWW Programme, (b) the observing component of the Global Atmosphere Watch Programme, (c) the WMO Hydrological Observing System of the Hydrology and Water Resources Programme, and (d) the observing component of the Global Cryosphere Watch, including both surface-based and space-based components, as illustrated in **Figure 5**. This includes all the WMO contributions to co-sponsored systems [such as GOOS, Global Climate Observing System [GCOS], the Global Framework for Climate Services (GFCS) and the GEOSS].

However, for physical and biogeochemical marine and ocean observations under the GOOS, it is important that all such contributions are linked into WIGOS, regardless of whether those observations are made by WMO members. This includes atmospheric and ocean observations made both at the sea surface and at depth from ships, buoys, tide gauges, profiling floats, as well as from emerging networks and platforms such as autonomous vehicles, animal borne sensors and HF radar. WMO is a partner with IOC in JCOMM and plays a key role in coordinating the sustained ocean observing system and its attendant data management structure, as well as ensuring appropriate links into and consistency with WIGOS.

WIGOS Identifiers

To do this effectively, it is essential to identify each observing platform (or station); this will be achieved through the specification of new, unique WIGOS identifiers that overcome many of the limitations (non-unique or changing with time) of previous identification schemes, such as land station identifiers, WMO numbers for data buoys or ship's call signs. In particular, WIGOS IDs will allow the relevant metadata to be ascribed to platforms, even when the characteristics of that platform may change with time (e.g., due to changes in sensor payload on a moored buoy). For marine and ocean observations, a convention for assigning and issuing unique WIGOS IDs has been agreed upon and will be applied across the JCOMM Observations Programme Area, where JCOMMOPS has delegated authority to issue such IDs at the behest of individual WMO members. This will avoid confusion, as has occurred for WMO terrestrial observing networks where different countries have developed a range of different approaches. In principle, WIGOS IDs can also be attributed to a wide range of third-party platforms for consistent identification, even when it is not possible (or permitted) to make these observations available through the WMO GTS [which is a component of the WMO Information System (WIS)]. Therefore, WIGOS IDs offer a globally applicable approach for identifying all observing platforms or stations across all domains.

Data Exchange Under WIGOS

The WIS is the global infrastructure covering WMO's telecommunications and data management functions and is a key element of WIGOS, as it provides an integrated approach for all WMO programs. It enables the routine collection and automated dissemination of observed data and products, as well as data discovery, access, and retrieval services for all data produced within the framework of WMO's programs. It builds upon the long-established GTS for exchange of data under the WWW but has been enhanced to permit exchanging large data volumes (such as satellite data, fine resolution Numerical Weather Prediction (NWP) products etc.) and delivering information to both NMHS and national disaster response authorities. It is worth noting that data exchanged on the WIS/GTS must be in approved WMO formats where, for time critical observational data, BUFR (Binary Universal Form for the Representation of meteorological data) is the standard. BUFR allows a wide range of data types (not just meteorological) and variables to be exchanged in a highly compressed manner, where BUFR templates are being developed to allow for the growing number of marine/ocean data types that are becoming

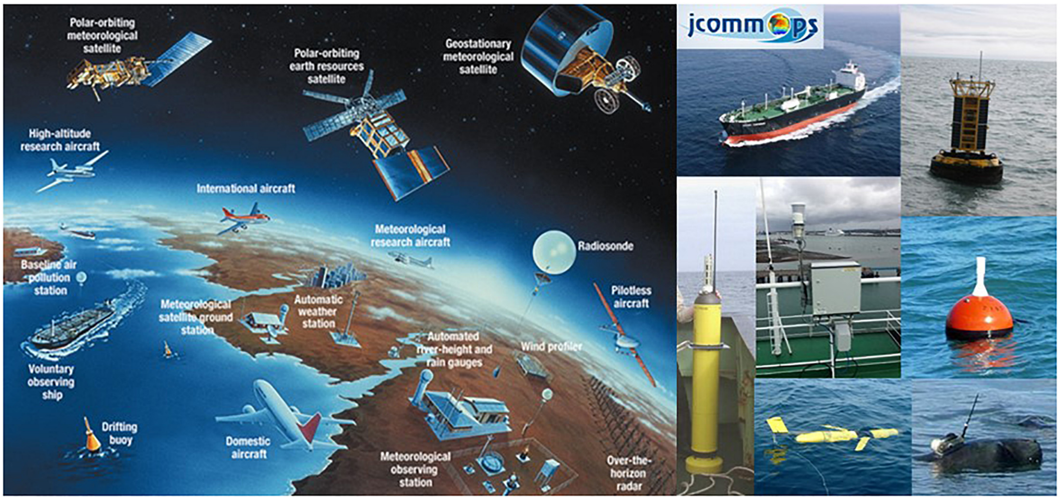


FIGURE 5 | (Left) schematic of the components of the WMO Global Observing System (© World Meteorological Organization) and **(right)** of the Global Ocean Observing System that presently contribute to WIGOS.

available. BUFR enables observational data to be exchanged at high precision, with attendant metadata and quality flags.

For medium range (out to several weeks ahead) and seasonal forecasting, the use of marine/ocean data in coupled ocean-atmosphere models has been standard practice for some time; however, marine/ocean data are becoming more important within the WMO community as NWP centers transition toward running coupled models also for weather prediction on shorter timescales. Biogeochemical ocean data from GOOS are also becoming increasingly required as more complete earth system models coupling the land surface, atmosphere, and ocean are developed for regional environmental predictions.

WIGOS Tools

Key to the success of WIGOS will be the development of tools such as the WMO Observing Systems Capability Analysis and Review (OSCAR) and the WIGOS Data Quality Monitoring System (WDQMS). These will allow end users to understand the observational data more completely and provide assurance that the observations are quality monitored, where problems are identified and addressed. OSCAR has three distinct, but interlinked, modules: OSCAR/Surface, OSCAR/Space and OSCAR/Requirements, which are openly accessible web-based tools[9] available to users, as discussed below.

OSCAR/Surface

Observing system capability analysis and review tool/surface is the official repository of metadata on surface-based meteorological and climatological observations exchanged internationally through the WIS. In the context of WIGOS, this means non-space-based, so it also includes metadata for subsurface ocean observations. However, it is recognized that more specific platform-related metadata are often available for many of the individual ocean networks (e.g., Argo) through their network-based metadata systems. Nevertheless, OSCAR/Surface provides for the first time the ability to search for metadata on a multitude of platforms, whether in the air, at the (land or sea) surface or below the surface, via a zoom-able and clickable interface, as illustrated in **Figure 6**. This includes both presently reporting stations (e.g., active floats and buoys) and non-reporting (e.g., expired floats and buoys, discontinued stations) platforms/stations. OSCAR/Surface allows the map to be filtered by network (GOOS, GCOS etc.), by platform/station type, station name, or WIGOS ID, so it provides a powerful web-based tool for accessing observational metadata across the full range of observations under WIGOS.

Generating the metadata remains the responsibility of the operators, and for marine and ocean-observing platforms and networks, these are submitted to JCOMMOPS through their web-based system. In turn, JCOMMOPS is tasked to quality control, harmonize and submit these data, in line with the WIGOS metadata standard to OSCAR/Surface via a machine-to-machine interface, thus relieving the operators of this responsibility.

OSCAR/Space

Observing system capability analysis and review tool/space is a resource provided by WMO in support of earth observation studies and global satellite mission coordination. The information provided is maintained by WMO in close cooperation with the space agencies and application experts. It provides detailed information on all earth observation satellites and instruments and presently contains information on over 200 satellite programs, over 500 satellites, and over 700 instruments. It allows the user to generate advanced queries on space-based capabilities (e.g., show all satellites planned in the period 2020–2060 in geostationary orbit, or show all currently flying instruments of a particular type). It can be used to review capability and generate gap analyses by variable and type of mission, as illustrated in **Figure 7** for sea surface salinity, which

[9]https://www.wmo.int/pages/prog/www/wigos/tools.html

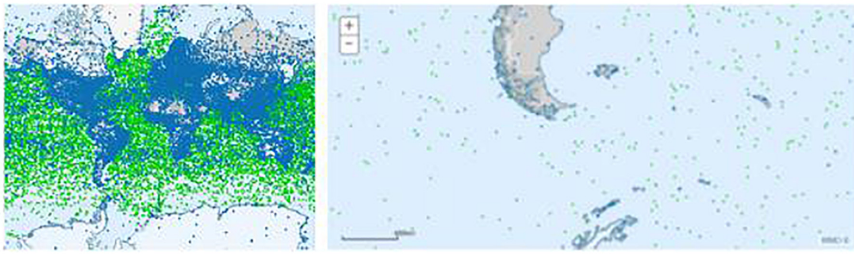
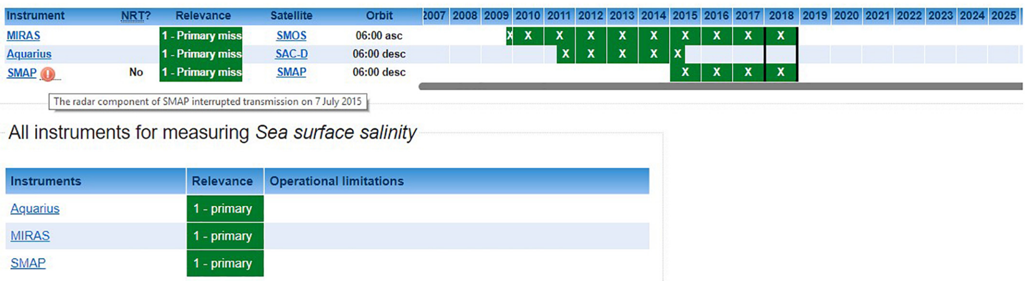


FIGURE 6 | OSCAR/Surface screen shots showing graphical maps showing platforms/stations for which metadata are available via mouse click (land/sea surface in blue, sub-surface in green).



Instrument	NRT?	Relevance	Satellite	Orbit	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
MIRAS		1 - Primary miss	SMOS	06:00 asc			X	X	X	X	X	X	X	X	X	X							
Aquarius		1 - Primary miss	SAC-D	06:00 desc					X	X	X	X	X										
SMAP	No	1 - Primary miss	SMAP	06:00 desc									X	X	X	X							

The radar component of SMAP interrupted transmission on 7 July 2015

All instruments for measuring *Sea surface salinity*

Instruments	Relevance	Operational limitations
Aquarius	1 - primary	
MIRAS	1 - primary	
SMAP	1 - primary	

FIGURE 7 | OSCAR/Space screen shot showing gap analysis for sea surface salinity.

shows expected end of capability in 2018 with no new missions planned at that time. The hyperlinks lead to detailed information on the platforms and sensors.

OSCAR/Requirements

Understanding the various user requirements for observational data is fundamental to the design and evolution of an integrated observing system, and the OSCAR/Requirements database provides the official repository of quantitative and technology free observations user requirements in support of the WMO and co-sponsored programs. WMO has defined its application areas, a number of which require marine/ocean observations: climate monitoring (including reanalysis), climate science, global NWP, high resolution NWP, nowcasting and very short range forecasting, seasonal to longer predictions and ocean applications (including marine services), each with its own user requirements.

The database contains the observational user requirements for around 300 different geophysical variables expressed in terms of six criteria: horizontal resolution, vertical resolution, observing cycle (periodicity), timeliness, uncertainty and stability. For each of these criteria, three values are determined: goal (the ideal capability above which further improvements are not necessary); threshold (the minimum requirement to be met to ensure that data are useful); and breakthrough (an intermediate level between threshold and goal, which, if achieved, would result in a significant improvement for the relevant application).

Where multiple WMO application areas require observations of the same physical variable in the same domain, they generally have different requirements. The OSCAR/Requirements database contains technology-free requirements for each of the WMO application areas and is reviewed on a regular basis to ensure that it remains extant. Assessment of what is feasible compared with the requirements results in a gap analysis, which together with the results of impact studies and expert knowledge, forms the basis for "statements of guidance" for each application; these are concise summaries of the gaps and deficiencies in the current capability and inform decision makers toward the evolution of the observing system. A fourth foreseen component, OSCAR/analysis, a collection of tools and services to support the gap analysis, is still in its infancy.

At present, the status of the ocean observing system is assessed by the status of individual networks against network-based metrics, e.g., spatial coverage of Argo floats or drifting buoys. However, most users, and the above application areas, are primarily concerned with the availability of data on one (or more) variables, e.g., surface air pressure and SST for NWP, wind and waves for maritime operations and coastal flood protection, SST and sub-surface SST for monitoring ocean heat content. Hence, there is an effort under the JCOMM OCG to develop variable-based metrics, which will be related to the user requirements of the appropriate application areas as defined within OSCAR.

WDQMS

As noted earlier, the WDQMS will help assure end users that the observations are quality monitored, where problems are identified and addressed. It has three basic functions: quality monitoring, evaluation, and incident management. WDQMS will use OSCAR/Surface as the source of metadata that describes the expected accuracy of the observational data. It aims to provide information on availability, timeliness, and quality of observations to data providers enabling them to take corrective actions as necessary.

Traditionally for marine observations under the WMO GOS, designated WMO monitoring centers that run global NWP models undertake the quality monitoring. Quality monitoring reports, e.g., observation minus model background statistics for VOS and buoy data, for various marine meteorological variables (surface air temperature and humidity, surface air pressure, wind speed and direction, and SST) are routinely generated as a by-product of NWP data assimilation systems. The statistics are typically published monthly. This is possible because there are sufficient observational data to allow the NWP models to generate a dynamically consistent background field, against which the most recent surface observations can be assessed. This alerts operators to platforms or stations generating suspect observations, where they can investigate and take appropriate action (e.g., withholding the erroneous data from the GTS until the problem has been remedied).

However, this approach is not feasible for subsurface observations, where there are too few observations available to the ocean models to generate a sufficiently reliable background field. Instead, the observations are used to validate the model, rather than the model background field being used to assess the quality of the observations. However, for subsurface temperature and salinity profile data, standard real-time quality control tests have been developed under the Argo program, and these tests are also applied to other profile data (e.g., from ship-based CTD measurements and marine mammal-borne sensors) where these data are distributed in real-time (or near real-time). Similarly, quality control tests have been developed for dissolved oxygen and are being developed for other biogeochemical variables, which will ensure that any such data distributed on the WIS or available through network-based GDACs (Global Data Assembly Centers) is of a minimum quality. However, for climate and scientific applications the collected data are subjected to more stringent delayed-mode quality checks that can identify whether there are any sensor drifts or offsets that need to be corrected for.

Concluding Remarks and Recommendations

World Meteorological Organization Integrated Global Observing System is a "system of systems", that provides a framework for all the WMO-sponsored and co- sponsored observing systems that encompasses *in situ* and remotely sensed observations, including those from GOOS. Integrating marine meteorological and oceanographic observations into the WIGOS is an essential activity that will lead to substantial benefits to the global meteorological community, as it will improve on the delivery of those data for use in a variety of application areas. Examples of these applications include the use of more sophisticated coupled ocean-atmosphere models for both shorter term weather forecasts and prediction of ocean hazards (tropical cyclones, storm surges, etc.) as well as for longer-term seasonal to climate predictions, and the provision of climate services under the GFCS. WIGOS will also be critical for climate monitoring; with the 2018 heat waves and other recent extremes, there is an enormous societal need to assess the current state of the climate against the climate of the recent past.

The benefits from WIGOS should not be restricted to the operational meteorological community. Many scientific studies require a range of ancillary data (i.e., in addition to that which is collected during research campaigns), and through the OSCAR tools, science users have the ability to interrogate the global data holdings across a wide range of domains to ensure that they can find and access the best available information. Hence, it is anticipated that WIGOS should benefit the entire global community that has a need for earth observation data. The "Vision for WIGOS in 2040" is presently being developed, envisaging how WMO members' user requirements for observational data may evolve over the coming decades. The long-time horizon is partly driven by the planning and implementation timescales for satellite and weather radar replacement programs and to ensure the surface-based and space-based components are complementary. In response to the WIGOS Vision 2040, which is expected to be adopted by the eighteenth World Meteorological Congress in mid- 2019, WMO will then develop a WIGOS Implementation Plan with clear recommended actions and guidance to WMO members and partners to make WIGOS component observing systems evolve in the most effective way in response to Earth System prediction requirements.

However, as previously noted WIGOS is about much more than system/network integration and covers standards and best practices, interoperability, operations, design, partnerships, monitoring and incident management, capacity development and outreach, all of which are relevant for the evolution of GOOS over the coming decade, where many of these themes have been touched upon earlier in this paper.

THE WAY AHEAD

Global Ocean Observing System now seeks to coordinate observations around the global ocean for three critical themes: climate, operational services, and marine ecosystem health. While much has been achieved since OceanObs'09, more needs to be done in the coming decade if GOOS is to realize its expanded vision and mission.

Within the context of the Framework for Ocean Observing, most of the effort to date has been focused on 'inputs' and 'processes,' i.e., setting requirements, specifying EOVs, improving observations coordination, and reinvigorating GRAs.

Focus now needs to shift to 'outputs' and 'outcomes.' The ocean observing system must clearly demonstrate and be widely recognized for its fundamental role underpinning the delivery of climate services, weather prediction, regional and global ocean assessments, fisheries management, ecosystem services, and real-time services.

In this paper, we have identified a field of opportunity for new collaborations to be formed— across regions, communities, and technologies. These include strengthened regional alliances, new observing networks, national ocean observing capabilities, *in situ* and satellite observations, and marine meteorology and oceanography.

To take advantage of these opportunities, this paper makes a number of suggestions and recommendations. Overall, the formal mechanisms of GOOS need to become more inclusive of ocean observing efforts relevant to its expanded vision and mission, and more creative in facilitating expansion and growth. This will require the formal mechanisms of GOOS to be adequately resourced.

AUTHOR CONTRIBUTIONS

TM wrote the Section "The Changing Context for GOOS – From OceanObs'09 to OceanObs'19." GN, CG, LG, ZW, ÁP, and TM wrote the Sections "Think Global, Act Local – Challenges and Opportunities in Collaborating Across GOOS Regional Alliances", "The Need for New Observations and Biological and Coastal Data to Meet Expanded Requirements for GOOS", and "Harnessing the Power of National Capabilities and Multinational Collaborations." H-MZ, EB, DL, RL, CM, KOB, KS, AS, DZ, and YZ wrote the Section "GOOS as a Mechanism for Partnership Between Global Satellite and *in situ* Programs." JT, SG, SB, EA, LR, CG, EC, MB, PP, and AR wrote the Section "Integrating Marine and Ocean Observations Into the Global Observing System."

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REFERENCES

Amin, R., Lewis, M. D., Lawson, A., Gould, R. W. Jr., Martinolich, P., Li, R. R., et al. (2015). Comparative analysis of GOCI ocean color products. *Sensors* 15, 25703–25715. doi: 10.3390/s151025703

Anderson, D. (2010). "Early successes: El Nino, Southern oscillation and seasonal forecasting," in *Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society*. (Venice).

Carse, F., Martin, M. J., Sellar, A., and Blockley, E. W. (2015). Impact of assimilating temperature and salinity measurements by animal-borne sensors on FOAM ocean model fields. *Q. J. R. Meteorol. Soc.* 141, 2934–2943. doi: 10.1002/qj.2613

Chatterjee, A., Gierach, M. M., Sutton, A. J., Feely, R. A., Crisp, D., Eldering, A., et al. (2017). Influence of El Niño on atmospheric CO_2 over the tropical Pacific Ocean: findings from NASA's OCO-2 mission. *Science* 358:eaam5776. doi: 10.1126/science.aam5776

Claustre, H., Bishop, J., Boss, E., Stewart, B., Berthon, J., Coatanoan, C., et al. (2009). "Bio-optical profiling floats as new observational tools for biogeochemical and ecosystem studies: potential synergies with ocean color remote sensing," in *Proceedings of the "OceanObs'09: Sustained Ocean Observations and Information for Society" Conference*. eds J. Hall, D. Harrison, and D. Stammer (Venice).

Dash, P., Ignatov, A., Kihai, Y., and Sapper, J. (2010). The SST quality monitor (SQUAM). *J. Atmos. Ocean. Technol.* 27, 1899–1917. doi: 10.1175/2010jtecho756.1

Drinkwater, M., Kwok, R., Geiger, C., Maslanik, J., Fowler, C., and Emery, W. (1999). *Ocean Observing System for Climate (OceanObs' 99)*. Available at: http://www.oceanobs09.net/work/oo99.php

EuroGOOS (2018). *Ocean Models: Catalogue of Existing Global, Regional and Coastal Ocean Models Generated from the GOOS Regional Alliances*. Available at: http://eurogoos.eu/models (accessed October, 24 2018).

Feely, R., Takahashi, T., Wanninkhof, R., McPhaden, M., Cosca, C., Sutherland, S., et al. (2006). Decadal variability of the air-sea CO2 fluxes in the equatorial Pacific Ocean. *J. Geophys. Res. Oceans* 111:C08S90.

Fischer, A., and Willis, Z. (2013). *Meeting Report of the Sixth Session of the GOOS Regional Alliance Forum (GRF-VI)*. Available at: http://ioc-goos.org/GRF-VI

Freeman, E., Woodruff, S. D., Worley, S. J., Lubker, S. J., Kent, E. C., Angel, W. E., et al. (2017). ICOADS release 3. 0: a major update to the historical marine climate record. *Int. J. Climatol.* 37, 2211–2232. doi: 10.1002/joc.4775

Geoghegan-Quinn, M., Fast, E., Jones, K., and Damanaki, M. (2013). *Galway Statement on Atlantic Ocean Cooperation: Launching a European Union – Canada – United States of America Research Alliance*. Available at: https://ec.europa.eu/research/iscp/pdf/galway_statement_atlantic_ocean_cooperation.pdf

GOOS (2015). *GRF-VII Review of GOOS Regional Alliances Survey*. Toronto, ON: GOOS.

GOOS (2016). *Report of the Fifth Meeting of the Global Ocean Observing System Steering Committee (GOOS SC-5)*. Toronto, ON: GOOS.

GOOS (2017). *Meeting Report of the Eighth Session of the GOOS Regional Alliance Forum (GRF- VIII)*. Toronto, ON: GOOS.

GOOS (2018a). *Global Ocean Observing System - Climate*. Available at: http://www.goosocean.org/index.php?option=com_content&view=article&id=3&Itemid=103 (accessed October 24, 2018).

GOOS (2018b). *Global Ocean Observing System - GOOS Regional Alliances (GRAs)*. Available at: http://www.goosocean.org/index.php?option=com_content&view=article&id=83:regional-alliances-gras-2&catid=24&Itemid=121 (accessed October 24, 2018).

GOOS (2018c). *Report of the Sixth Meeting of the Global Ocean Observing System Steering Committee (GOOS SC-6)*. Toronto, ON: GOOS.

Gruber, N., Doney, S., Emerson, S., Gilbert, D., Kobayashi, T., Körtzinger, A., et al. (2010). "Adding oxygen to Argo: developing a global in-situ observatory for ocean deoxygenation and biogeochemistry," in *Proceedings of OceanObs 9*. (Venice).

Huang, B., Angel, W., Boyer, T., Cheng, L., Chepurin, G., Freeman, E., et al. (2018). Evaluating SST analyses with independent ocean profile observations. *J. Climate* 31, 5015–5030. doi: 10.1175/jcli-d-17-0824.1

Huang, B., Thorne, P. W., Banzon, V. F., Boyer, T., Chepurin, G., Lawrimore, J. H., et al. (2017). Extended reconstructed sea surface temperature, version 5 (ersstv5): upgrades, validations, and intercomparisons. *J. Climate* 30, 8179–8205. doi: 10.1175/jcli-d-16-0836.1

IOC-UNESCO (2013). *GOOS Regional Policy 2013*. Available at: https://unesdoc.unesco.org/ark:/48223/pf0000226859.

IOC-UNESCO (2015). *Review of the GOOS Regional Alliances (GRA) Survey*. Available at: http://www.ioc-unesco.org/index.php?option=com_oe&task=viewDocumentRecord&docID=22373

IOC-UNESCO (2018). *Global Ocean Observing System - In Situ Networks*. Available at: http://www.goosocean.org/index.php?option=com_content&view=article&id=24&Itemid=12 3

Jager, J., and Ferguson, H. (1991). "Climatic change: science, impacts and policy," in *Proceedings of the 2nd World Climate Conference, Geneva, October–November 1990*. (Cambridge: Cambridge University Press).

JCOMM (2018). *Observations Programme Area*. Available: https://www.jcomm.info/index.php?option=com_content&view=article&id=338&Itemid=38 (accessed October 24, 2018).

Land, P., Bailey, T., Taberner, M., Pardo, S., Sathyendranath, S., Nejabati Zenouz, K., et al. (2018). A statistical modeling framework for characterising uncertainty in large datasets: application to ocean colour. *Remote Sens.* 10:695. doi: 10.3390/rs10050695

Landschützer, P., Gruber, N., and Bakker, D. C. E. (2016). Decadal variations and trends of the global ocean carbon sink. *Glob. Biogeochem. Cycles* 30, 1396–1417. doi: 10.1002/2015gb005359

Legler, D. M., and Hill, K. (2014). Tropical Pacific observing for the next decade: tropical pacific observing system (TPOS) 2020 Workshop La Jolla, California, 27–30 January 2014. *Eos Trans. Am. Geophys. Union* 95, 196–196. doi: 10.1002/2014EO230006

Lindstrom, E., Gunn, J., Fischer, A., McCurdy, A., and Glover, L. (2012). *A Framework for Ocean Observing: A Report By the Task Team for an Integrated Framework for Sustained Ocean Observing*. Paris: UNESCO.

Martin, M., Dash, P., Ignatov, A., Banzon, V., Beggs, H., Brasnett, B., et al. (2012). Group for high resolution sea surface temperature (GHRSST) analysis fields inter-comparisons. Part 1: a GHRSST multi-product ensemble (GMPE). *Deep Sea Res. Part II Top. Stud. Oceanogr.* 7, 21–30. doi: 10.1016/j.dsr2.2012.04.013

Martínez-Vicente, V., Evers-King, H., Roy, S., Kostadinov, T. S., Tarran, G. A., Graff, J. R., et al. (2017). Intercomparison of ocean color algorithms for picophytoplankton carbon in the ocean. *Front. Mar. Sci.* 4:378. doi: 10.3389/fmars.2017.00378

Maturi, E. M. (2010). "A new ultra high resolution sea surface temperature analysis from GOES-R ABI and NPOESS VIIRS," in *Proceedings of the 6th Annual Symposium on Future National Operational Environmental Satellite Systems-NPOESS and GOES-R)*. (Atlanta).

Miloslavich, P., Palacz, A., Lorenzoni, L., Sierra-Correa, P., Arias-Isaza, F., and Nolan, G. (2018). *Report of the GOOS South American Regional Workshop: Regional projects and national strategies on marine monitoring*. Available at: http://www.goosocean.org/index.php?option=com_oe&task=viewDocumentRecord&docID=22369

Moedas, C., Pandor, N., and Kassab, G. (2017). *Belem Statement on Atlantic Research and Innovation Cooperation*. Available at: https://ec.europa.eu/research/iscp/pdf/galway_statement_atlantic_ocean_cooperation.pdf

Reynolds, R. W., Rayner, N. A., Smith, T. M., Stokes, D. C., and Wang, W. (2002). An improved in situ and satellite SST analysis for climate. *J. Climate* 15, 1609–1625. doi: 10.1175/1520-04422002015<1609:Aiisas<2.0.Co;2

Rintoul, S., Speer, K., Sparrow, M., Meredith, M., Hofmann, E., Fahrbach, E., et al. (2010). "Southern ocean observing system (SOOS): rationale and strategy for sustained observations of the Southern Ocean," in *Proceedings of OceanObs '09: Sustained Ocean Observations and Information for Society*. (Venice).

Smith, T. M., Reynolds, R. W., Peterson, T. C., and Lawrimore, J. (2008). Improvements to NOAA's historical merged land–ocean surface temperature analysis (1880–2006). *J. Climate* 21, 2283–2296. doi: 10.1175/2007jcli2100.1

WMO (2013). *WIGOS (WMO Integrated Global Observing System). Implementation Plan for the Evolution of Global Observing Systems (EGOS-IP)*. Geneva: WMO.

WMO (2017). *Guide to the WMO Integrated Global Observing System*. Geneva: WMO.

Xu, F., and Ignatov, A. (2014). In situ SST quality monitor (i Quam). *J. Atmos. Ocean. Technol.* 31, 164–180. doi: 10.1175/jtech-d-13-00121.1

Yang, W., John, V., Zhao, X., Lu, H., and Knapp, K. (2016). Satellite climate data records: development, applications, and societal benefits. *Remote Sens.* 8:331. doi: 10.3390/rs8040331

Zhang, H., Reynolds, R., and Bates, J. (2006). "Blended and gridded high resolution global sea surface wind speed and climatology from multiple satellites: 1987 - Present," in *Proceedimgs of the 86th AMS Annual Meeting*. (Atlanta, CA).

Zhang, H. M., Reynolds, R. W., Lumpkin, R., Molinari, R., Arzayus, K., Johnson, M., et al. (2009). An integrated global observing system for sea surface temperature using satellites, and in situ data: research to operations. *Bull. Am. Meteorol. Soc.* 90, 31–38. doi: 10.1175/2008bams2577.1

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Animal-Borne Telemetry: An Integral Component of the Ocean Observing Toolkit

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Animal telemetry is a powerful tool for observing marine animals and the physical environments that they inhabit, from coastal and continental shelf ecosystems to polar seas and open oceans. Satellite-linked biologgers and networks of acoustic receivers allow animals to be reliably monitored over scales of tens of meters to thousands of kilometers, giving insight into their habitat use, home range size, the phenology of migratory patterns and the biotic and abiotic factors that drive their distributions. Furthermore, physical environmental variables can be collected using animals as autonomous sampling platforms, increasing spatial and temporal coverage of global oceanographic observation systems. The use of animal telemetry, therefore, has the capacity to provide measures from a suite of essential ocean variables (EOVs) for improved monitoring of Earth's oceans. Here we outline the design features of animal telemetry systems, describe current applications and their benefits and challenges, and discuss future directions. We describe new analytical techniques that improve our ability to not only quantify animal movements but to also provide a powerful framework for comparative studies across taxa. We discuss the application of animal telemetry and its capacity to collect biotic and abiotic data, how the data collected can be incorporated into ocean observing systems, and the role these data can play in improved ocean management.

Keywords: ocean observing, animal telemetry, animal movement, movement analysis, EOV

BACKGROUND

Animal telemetry is a powerful tool for observing marine animals and their environments (Bograd et al., 2010; Costa et al., 2010a,b, 2012; Hussey et al., 2015). Animal telemetry can provide important ecological insights into animals' habitat preferences and home range sizes (Aarts et al., 2008; Block et al., 2011; Raymond et al., 2015), behavior states (Jonsen et al., 2005), physiology (Metcalfe et al., 2012), the timing of long-term movements and migrations (McConnell and Fedak, 1996; Hays et al., 2006; Shaffer et al., 2006; Aarestrup et al., 2009; Cherry et al., 2013; Whitlock et al., 2015), and the biotic and abiotic factors that shape their current and potential abundances and distributions (Laidre et al., 2008; Hawkes et al., 2009; Costa et al., 2010b; Hazen et al., 2013a,b; Hindell et al., 2016). These ecological parameters can be monitored to provide insight into changes in the underlying state of the oceans and their ecosystems (Hazen et al., 2019).

In addition to these ecological insights, there has been growing acceptance by physical oceanographers that animal-borne sensors can provide useful abiotic data from regions otherwise difficult to sample (Boehlert et al., 2001; Charrassin et al., 2008; Fedak, 2013; Ohshima et al., 2013). For example, assimilating animal telemetry data into ocean circulation models has resulted in significant improvements in representations of major ocean systems (Roquet et al., 2013; Treasure et al., 2017). While animal-borne sensors are limited to where animals go, and therefore, do not provide the same spatial and temporal coverage as artificial observing systems, the broad scope and immense data collection capabilities [e.g., multiple Conductivity Temperature Depth (CTD) casts per day] provide a uniquely valuable opportunity for collaboration among biologists and earth scientists to promote improved observation of ocean systems (Fedak, 2004).

Many streams of animal-borne telemetry data are now routinely included in online data portals that are available to researchers in a broad range of scientific fields. We contend that these data streams provide reliable observations of Essential Ocean Variables (EOVs). For example, the Global Ocean Observing system (GOOS) is interested in surface and sub-surface temperature and salinity profiles provided by animal-borne sensors, as these variables are crucial for the detection and attribution of changes in the marine environment that are relevant on a global scale.

At the OceanObs Conference in 2009, the potential of animal borne sensors for ocean observation was well received, including their role in collecting observations of EOVs (Costa et al., 2010a). In the decade since this meeting, the application of animal borne sensors has further matured, and the use of animal telemetry continues to grow exponentially (Hussey et al., 2015). This has been made possible by advances in tag technology, including miniaturization, improvements in battery efficiency and memory capability, and large reductions in unit costs. These advances are being complemented by an expanding range of sophisticated sensors that provide unprecedented insight into the lives of marine animals and their environments, from coastal and continental shelf ecosystems through to polar seas and open oceans (Guinet et al., 2013; Kays et al., 2015; Lennox et al., 2017). In this paper, we (1) review the status of animal telemetry systems in the context of global ocean observing, (2) describe current and new applications of this technology for marine ecological studies and collection of ocean observations including EOVs, and (3) review new approaches to analyzing these increasingly large and complex data sets, and comment on future directions.

AN OVERVIEW OF ANIMAL TELEMETRY SYSTEMS

There are several animal telemetry technologies that are used to collect data in the marine environment (**Figure 1**). Some systems are archival, collecting streams of data (e.g., an animal's location, physiological and behavioral states, and environmental conditions) and storing them on the tag for later recovery of the device. Other systems are able to relay data via radio (e.g., satellite) or acoustic signals.

Archival tags are generally used for animals that are able to be easily recaptured. These include central-place foragers, such as seabirds and pinnipeds, that return to a known location either between foraging trips or after longer migrations. Body size and attachment technique may also necessitate the use of archival tags, which are often smaller than relay tags due to lower power requirements. In cases where tags are less likely to be recovered or where near real-time information is desired, data may still be archived on the tag, but are also relayed periodically through data transfer systems. For air-breathing species, such as marine mammals, seabirds and turtles, radio or satellite tags attempt to relay data each time the animal surfaces, via an antenna that must be exposed to the air. For non-air-breathing species, tags can be fitted on a dorsal fin or attached with tethers, so that the antenna occasionally emerges from the water when the animal swims near the surface. For animals that never surface, a pop-up archival tag can be deployed, which logs information for extended periods before "popping off" when a triggering mechanism releases the tag from the animal. The tag then floats to the surface where it can transmit data to a satellite (Block et al., 1998; Block, 2005). Depending on the size of the package, archival tags range from simple coarse resolution location data (Global Location Sensing-GLS) to high resolution (Global Positioning System-GPS) location data with multiple ancillary sensors (e.g., depth, temperature, conductivity, dissolved oxygen, accelerometry, see **Figure 1**).

Satellite-relay systems have limited bandwidth and are, therefore, often unable to transmit all of the large volumes of data that sophisticated, multiple sensor tags collect and archive. This constraint is a function of tag energy requirements, the amount of time an animal spends at the surface, i.e., access to a satellite, and satellite availability. Therefore, these tags often transmit either a pre-programmed data summary (e.g., average values over preselected time periods), or a random subsample of detailed data (Fedak et al., 2002; Block et al., 2011), whenever their signals reach a satellite. Consequently, there is a significant benefit in recovering tags where possible, to access the full stream of high-resolution archived data.

Acoustic telemetry is widely used for small marine animals that do not surface to breathe and are unlikely to be reliably recaptured (Donaldson et al., 2014). Typically, acoustic transmitters are small, light, implantable and cost-effective, facilitating large sample sizes. However, acoustic telemetry is limited by the fact that data transmission occurs through the water via acoustic data packages that can only be detected within the range of a receiver (rarely > 800 m). In most cases, receivers must also be physically recovered from the ocean to download the archived data, limiting real time data acquisition. However, units that transmit data from receivers over mobile phone networks, or via satellite telemetry, are becoming increasingly common, paving the way for the development of novel observation platforms especially in near-shore regions. Mobile acoustic receivers mounted on gliders (Lennox et al., 2018) or attached to free-swimming animals (Lidgard et al., 2014) are also now starting to be deployed, increasing the spatial coverage of the acoustic network. Emerging coordination among research organizations with compatible receivers enables acoustic telemetry data to be linked across scales of tens of meters to thousands of kilometers (Heupel et al., 2006; Brodie et al., 2018; Griffin et al., 2018).

ANALYSIS OF ANIMAL TELEMETRY DATA FOR MOVEMENT ECOLOGY

A variety of methods have been used to analyse different types of animal telemetry data. For example, for satellite telemetry and light-level geolocation, state-space models (Patterson et al., 2008; Schick et al., 2008; Jonsen et al., 2013; McClintock et al., 2014), including hidden Markov models (e.g., Langrock et al., 2012), have been widely used to infer animal movements and to quality-control locations from error-prone telemetry data (Jonsen et al., 2005; Johnson et al., 2008). Such models allow inference of unobservable states or behaviors (e.g., horizontal location, foraging bouts) from time-series observations. Simultaneously, these models separate variability arising from an animal changing speed and direction as it moves through different habitats, from artificial noise introduced by the observation process (e.g., through the distortion or disruption of animal-borne tag transmissions to an orbiting satellite). State-space models have been used to advance knowledge based on large telemetry datasets (Block et al., 2011; Strøm et al., 2018), to infer unobservable behaviors (Leos-Barajas et al., 2017; Michelot et al., 2017), and to understand how movement behaviors are influenced by environmental drivers (Patterson et al., 2009; McClintock et al., 2012; Bestley et al., 2013; Jonsen et al., 2018).

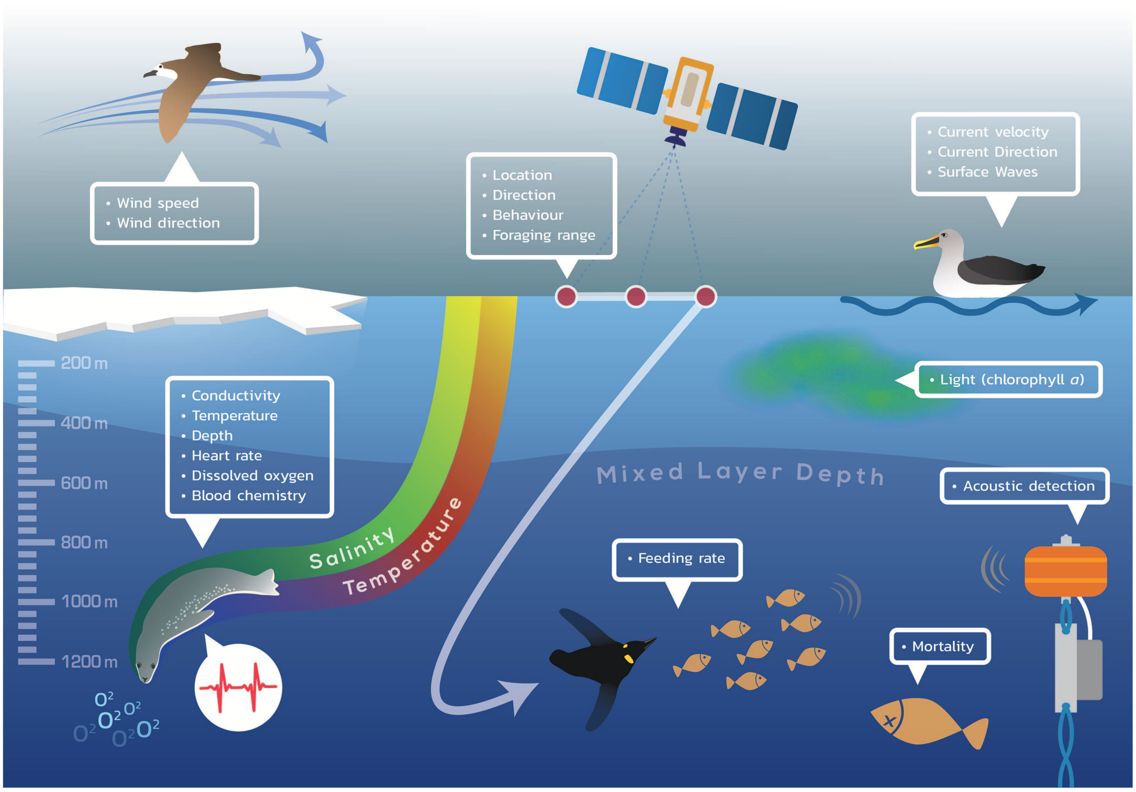

FIGURE 1 | Schematic illustrating the many parameters that can be measured by animal-borne packages, using archival, acoustic, or satellite telemetry. The environmental, physiological, and ecological data collected by the illustrative marine animals (penguin, seabird, fish, seal) may be measured in multiple ways and stored or transmitted or both.

Movement behaviors of mobile marine animals, such as foraging, resting, or fleeing, can be embedded in a complex web of movement types (straight line, looping, convoluted paths). The random walk paradigm, a standard framework for modeling individual animal movement, has also been commonly used to describe these movement patterns and to infer behaviors from simple null models that relate to theories about searching, foraging or dispersal (Nathan et al., 2008). Normally diffusing random walks, such as a correlated random walk (CRW) (Turchin, 1998), can be used to analyze navigational capacities (Bailey et al., 2018) and movements in heterogeneous landscapes (Barton et al., 2009), to test habitat selection (Sims et al., 2006), to infer behavioral states from movement paths (Jonsen et al., 2005) and as a means to aid reconstruction of marine animal paths from telemetry data (Johnson et al., 2008).

Resource Selection Functions (RSF) in random-walk models, which have been widely used to investigate species' habitat preferences in terrestrial studies, are now an emerging approach in marine ecology (Manly et al., 2002; Sousa et al., 2016; Lone et al., 2018). The objective of RSFs is to quantify the disproportionate use of a resource (or habitat) relative to its availability, often estimated by mechanistic movement models (Bastille-Rousseau et al., 2015; Queiroz et al., 2016). Improvements have also been made to RSFs, such as the addition of step- and path-selection and the estimation of movement covariates within step selection analysis, thus accounting for changes in resource availability during animal movement (Avgar et al., 2016).

Specialized random walks, including Lévy walks (Sims et al., 2008), have been used to explore commonalities in movement and potential optimality of search patterns by individuals and species across different environments (Humphries et al., 2010). A strength of quantitative random walk analysis is the opportunity it presents for testing explicit hypotheses linked to elucidating the factors driving the expression and evolution of behavior (Hays et al., 2016).

Studies using acoustic telemetry have historically been designed to generate data over limited spatial scales to address a specific research question. These studies have addressed measures of residency, movements and activity space (Heupel et al., 2006). Analyzing data over small spatial scales limits the capacity of researchers to make comparisons of patterns among study sites and to link data from the same individuals that may move among telemetry arrays. The development of broader acoustic telemetry networks and increased data sharing has resulted in vast data sets that can provide broader information on species movement (e.g., Hoenner et al., 2018). These large data sets provide challenges in data management and analysis, especially when considering that these data are typically used to calculate movement metrics, such as home range size. Standardized approaches that calculate metrics of detection, dispersal and activity space allow direct comparisons among sites Udyawer et al. (2018). Integration of multiple data streams, such as environmental variables, to help interpret movements and space-use, also enhance the value of telemetry data but present new analytical and data management challenges (see below). Finally, technological advances, including sensors integrated into transmitters, provide another layer of data complexity, while concomitantly providing an opportunity to develop a refined sense of movement in three dimensions (Simpfendorfer et al., 2012; Udyawer et al., 2015; Lee et al., 2017).

ANIMAL TELEMETRY AND OCEANOGRAPHY

Animal telemetry has contributed data on key physical environmental variables, including ocean temperature and salinity, by using oceanographic sensors integrated into animal-borne satellite transmitters. Tracked marine animals are gathering key surface and sub-surface oceanographic information in some of the harshest environments on the planet, filling important observational gaps in the global climate observing system (Fedak, 2013; Roquet et al., 2013, 2017), while simultaneously linking the behavior of these animals to these oceanographic parameters (Biuw et al., 2007). Vertical profiles of temperature and salinity, the two key observations for calculating water density are now routinely sampled in several key areas of the global ocean, such as the seasonally ice-covered sectors of the Southern Ocean (Charrassin et al., 2008). These data are central to understanding global climate processes given this region's central role in heat and CO2 uptake and unhindered (land barrier free) distribution of climate signals (Sallée, 2018). New sensors also provide expanding opportunities to monitor additional parameters, such as chlorophyll (Guinet et al., 2013) or the wind/wave surface state from accelerometry and magnetometry or hydrophony (Cazau et al., 2017). The current state of development and some of the limitations of integrating animal telemetry with oceanography are reviewed below, with specific focus on advances in technology and scientific findings.

Autonomous Oceanography With Animal-Borne Sensors

Physical oceanography has traditionally focused on the observation of the two key properties of seawater: temperature and salinity. These parameters are related to the ocean heat budget, a central element of the climate system, as well as to mechanisms of evaporation, precipitation, and sea ice formation and melting. When observed simultaneously, these two properties determine seawater density from which the geostrophic component of ocean circulation, the vertical stratification of water masses and mixing patterns can be derived. For this reason, temperature and salinity are most often profiled together using a single instrument, the CTD (Conductivity-Temperature-Depth), that combines a pressure sensor with a temperature probe and a conductivity cell from which salinity and density can be derived. Traditionally, these instruments have been deployed from research vessels.

The advent of the global Argo array of autonomous profiling floats in the early 2000s profoundly modified ocean monitoring. The Argo system provides a synoptic sampling of the upper 2000 m of the ocean in space and time that is near global albeit at a coarse scale (Roemmich et al., 2009; Riser et al., 2016). Concurrently, in 2000/01, the Sea Mammal Research Unit (SMRU, University of St. Andrews, UK) developed the CTD Satellite Relay Data Logger (CTD-SRDLs **Figure 2**; Lydersen et al., 2002). The CTD-SRDL is an autonomous logger incorporating a miniaturized CTD unit (Boehme et al., 2009), coupled with a satellite transmitter (Argos) that enables geo-location and data transmission. Calibration of the sensors in a labeled oceanographic calibration facility is undertaken prior to every deployment to ensure high data quality [for example following battery replacement (Goetz, 2015)]. The CTD-SRDL is most often programmed to sample water properties at 0.5 Hz during the ascent phase of an animal's dive and these CTD-profiles are then telemetered in a compressed form (binned in from 10 to 25 depth levels per profile depending on the configuration) using the ARGOS location and data collection system (Photopoulou et al., 2015), offering a life-span of about 6 to 8 months of data collection/transmission, depending on the species tagged and the scheduling applied.

Although there have been important modifications in the design and programming of CTD-SRDLs since their first use, the design of the CTD instruments incorporated in these tags has remained quite stable. This stability has ensured accumulation of data and improved knowledge about each of the sensors' performance, based on both laboratory calibration experiments (Boehme et al., 2009) and comparisons with ship-borne CTD profiles (Roquet et al., 2011; Frazer et al., 2018; Mensah et al., 2018). More recently, continuous recording by CTD-SRDL sensors has enabled direct comparisons between consecutive upcasts and downcasts, thereby providing new ways to assess the dynamic response of sensors (Mensah et al., 2018).

FIGURE 2 | A CTD-SRDL tag, featuring a miniaturized CTD on top of the core unit, with the microcontroller below, the wet/dry sensor on the frontside, the battery on the rear, and the Argos antenna pointing forward.

The SMRU CTD-SRDL and other loggers archive data to internal memory far more frequently than they can be transmitted and, if the instruments can be recovered, additional data at higher resolution can be downloaded. To date, about 50 finely-resolved multi-parameter tracks have been collected from polar seals [Weddell (*Leptonychotes weddellii*), crabeater (*Lobodon carcinophagus)* and southern elephant seals (*Mirounga leonina)*], and temperate pinnipeds [Australian (*Neophoca cinerea*) and California (*Zalophus californianus*) sea lions, Australian (*Arctocephalus pusillus doriferus)* and New Zealand fur seals (*A. forsteri*)]. In some rare instances, CTD-SRDLs have been configured to continuously log during the entire deployment period on southern elephant seals from the Kerguelen Islands. Results from a dozen such loggers offered a kilometric spatial resolution to investigate sub-mesoscale variability, as well as new opportunities to investigate CTD data quality (Mensah et al., 2018).

Oceanographic Findings Enabled by Animal Telemetry Over the Last Decade

The functionality of Argo floats is limited in polar regions due to the seasonal presence of sea ice that prevents floats from returning to the surface. Instrumenting free-ranging, air-breathing animals that move through sea-ice covered areas, such as seals, with temperature and salinity sensors can help fill data gaps in the Argo dataset in sea ice regions (Fedak, 2013; Treasure et al., 2017). To date, over 540 000 profiles have been collected by marine mammals and have been made available to the broader operational and research oceanography communities (Roquet et al., 2014) (**Figure 3**, http://www.meop.net/).

The great potential provided by animal-borne sensors for monitoring Southern Ocean hydrographic conditions and how animals respond to them was demonstrated following the deployments of CTD-SRDLs on southern elephant seals in 2004–2005 (Biuw et al., 2007; Charrassin et al., 2008). These early data helped refine our knowledge of the Antarctic Circumpolar Current (ACC) frontal structure and hydrography in the South Atlantic (Boehme et al., 2008; Meredith et al., 2011) and in the vicinity of the Kerguelen Plateau (Park et al., 2008; Roquet et al., 2009) with applications for tracking ACC fronts (Pauthenet et al., 2018) or for estimating rates of sea ice formation (Charrassin et al., 2008; Williams et al., 2011). In 2011, observations from animal-borne CTD-SRDLs were central to solving a 30^{+} year-old puzzle regarding Antarctic Bottom Water formation in the Weddell-Enderby Basin (Ohshima et al., 2013). Observations of very high salinity shelf water were linked to a new source of Antarctic Bottom Water in the intense Cape Darnley polynya. Furthermore, Williams et al. (2016) demonstrated that Prydz Bay, situated just east of Cape Darnley, makes a secondary contribution to Antarctic Bottom Water due to the production of dense shelf water near the Amery Ice Shelf (also see Xu et al., 2017). A minor source of Antarctic Bottom Water was also detected at Vincennes Bay (Kitade et al., 2014), supporting the idea that several East Antarctica polynyas contribute to Antarctic Bottom Water formation. However, the ongoing freshening by glacial melting may compromise the ability of polynyas to form this Bottom Water in the future (Williams et al., 2016; Silvano et al., 2018).

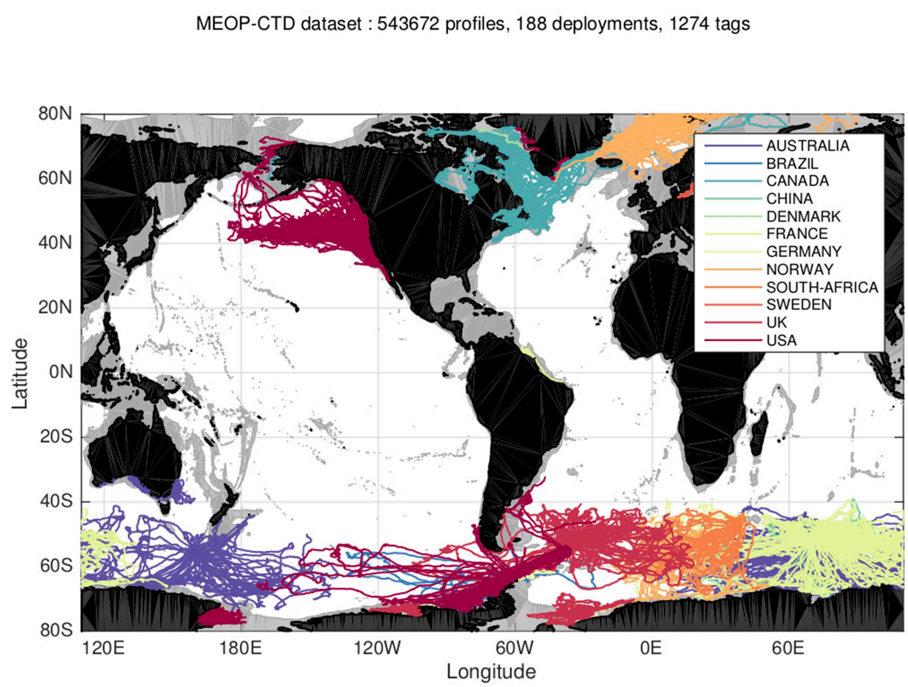

FIGURE 3 | Distribution of hydrographic profiles currently available in the MEOP-CTD database (November 2017 version, Source: meop.net).

Animal-collected data have also been very successful in documenting local circulation and seasonal variability of water properties over the Antarctic continental shelf. Costa et al. (2008) analyzed the upper ocean heat content variability in the west Antarctic Peninsula using instrumented seals, providing a valuable reference to evaluate numerical circulation models. Using the maximum depth of benthic dives, Padman et al. (2010) identified troughs in the continental shelf that allow intrusions of Circumpolar Deep Water under the Wilkins Ice Shelf, accelerating its collapse (Padman et al., 2012). Animal-collected data also helped to characterize the exchange of properties across the shelf break in the Weddell Sea, linked to eddy overturning (Nost et al., 2011) and wind forcing variability (Arthun et al., 2012). Zhang et al. (2016) described intrusions of modified Circumpolar Deep Water into the continental shelf waters of the Bellingshausen Sea, with important implications for the stability of the West Antarctic Ice Sheet. Mallett et al. (2018) presented new insights on the distribution and seasonality of Circumpolar Deep-Water properties in the Amundsen Sea. More broadly, the animal collected data is limited seasonally and spatially, but by merging animal-collected data with ship-based and Argo float observations, Pellichero et al. (2017) provided the most comprehensive assessment of the seasonal cycle of Southern Ocean mixed-layer characteristics to date.

Animal CTD-SRDLs have also become a valuable data source in several sectors of the North Atlantic Ocean. Straneo et al. (2010) used hooded seal (*Cystophora cristata*) data from the East Greenland Shelf to estimate seasonal temperature variations of subtropical waters sitting near the entrance of a major glacial fjord. Variability of these continental shelf waters was further investigated by Sutherland et al. (2013). Instrumented ringed seals (*Pusa hispida*) have also proved useful to investigate freshwater runoff from the Greenland Ice Sheet (Mernild et al., 2015) and freshwater discharge plumes from glaciers in Greenland (Everett et al., 2018) by providing observations from directly adjacent to the glacier tongue. Grist et al. (2011) used Argo and marine mammal profiles to produce a gridded data set that revealed distinctive boundary current-related temperature minima in the Labrador Sea and at the East Greenland coast (Isachsen et al., 2014). Isachsen et al. (2014) used data collected by instrumented hooded seals as well as Argo floats to reveal warmer and saltier conditions over much of the Nordic Seas in 2007–2008 compared to the 1956–2006 climatology. Exchanges of warm Atlantic Water across the shelf west of Spitsbergen were found to be primarily controlled by surface heat flux through the generation of an eddy overturning (Tverberg et al., 2014).

Autonomous Sensing of the Air-Sea Interface With Seabirds

The air-sea interface couples the ocean and atmosphere through exchanges of momentum, heat, gas, water, and micro-particles, thus it plays an important role in determining daily weather

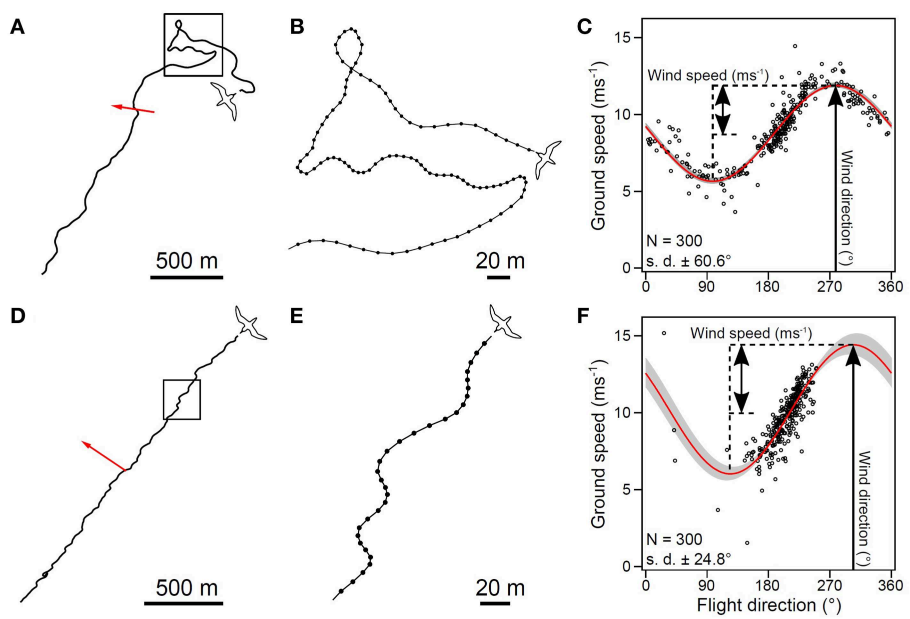

FIGURE 4 | (A) An example of a 5-min section of the flight path of a streaked shearwater. The red arrow indicates the estimated wind velocity. **(B)** Enlarged view of a meandering path shown in **(A)**. **(D)** Another example of a 5-min section of a flight path of a streaked shearwater when the bird seemed to travel in a certain direction. **(E)** Enlarged view of **(D)** showing repeated zigzag movement from a soaring maneuver. **(C,F)** The relationship between flight direction and ground speed of the path section in **(A)** [estimated wind speed of fitted curve, 3.11 m s^{-1}; upper confidence interval (CI), 3.13 m s^{-1}; and lower CI, 3.10 m s s^{-1}; estimated wind direction of fitted curve, 278°; upper CI, 280°; and lower CI, 277°] and D (estimated wind speed of fitted curve, 4.20 s^{-1}; upper CI, 4.34 s^{-1}; and lower CI, 4.10 s^{-1}; estimated wind direction of fitted curve, 304°; upper CI, 310°; and lower CI, 298°), respectively. Angular SDs of the flight direction are **(C)** 60.6° and **(F)** 24.8°, respectively. The red curve is the fitted sinusoidal curve. Gray area represents the 95% CI of the fitted sinusoidal curve. Estimated wind speed and direction is indicated by black arrows. The figures adapted from data presented in Yonehara et al. (2016).

conditions and also in driving global climate change and biogeochemical cycles. Wind and current observations are necessary to understand the processes mediated at this interface. Although there have been remarkable advances in technology to observe the air-sea interface such as satellites, drifters, and autonomous surface vehicles, measurements have been so coarse spatially or temporally that the air-sea fluxes often remain uncertain, decreasing the accuracy of forecasting unusual weather events. Physical observing approaches that sample at fine spatio-temporal resolutions are required to improve the accuracy of atmosphere and ocean nowcasts and forecasts.

The development of a small motion logger that can be attached to a bird's back and contains a micro-controller, a GPS receiver, an inertial sensor, a 3-axis geomagnetic sensor, and a Li-Ion battery charger (Yoda et al., 2014; Yonehara et al., 2016) has revealed that observations of soaring seabirds, such as the streaked shearwater (*Calonectris leucomelas*) and albatross, can measure winds over the sea (Yonehara et al., 2016; Goto et al., 2017; **Figure 4**), surface currents (Yoda et al., 2014), and surface waves. Winds are particularly under-sampled in open ocean areas due to infrequent (twice/day) satellite observations and sparse buoy measurements, and in coastal zones where the topography is complex (Pickett et al., 2003; He et al., 2004; Albert et al., 2010). Extensive travel distance and prolonged flight duration of soaring seabirds enabled fine-scale resolution and wide geographic range estimation of wind speed and direction covering temporal and spatial gaps between the remote-sensing measurements.

Surface currents consist of geostrophic and ageostrophic currents, such as Ekman and Stokes drifts, which play important roles in transporting heat, organic matter, and inorganic matter, and therefore strongly influence marine ecosystems. Current measurements are typically conducted by *in situ* observations using either ship-board acoustic Doppler current profilers (ADCP), moored current-meters, Lagrangian drifters, or remote-sensing, such as satellite altimetry and High Frequency (HF) radar. However, these *in situ* methods have spatial or temporal limitations and HF radar observation in particular is limited to coastal regions. Satellite altimetry offers wider spatial scope for observations and can observe global surface geostrophic currents, but has disadvantages including spatial and temporal resolutions of 7 km and 10 days, respectively. Accuracy of altimetry decreases in the coastal regions due to tidal effects and importantly, satellite altimetry cannot measure ageostrophic currents.

Yoda et al. (2014) developed a new method to measure *in situ* currents by exploiting the behavior of seabirds equipped with GPS loggers. This method estimated surface current velocity from GPS track data collected by streaked shearwaters when they drifted passively at the sea surface (**Figure 5**). The GPS logger consisted of a GPS receiver with an antenna (GiPSy, Technosmart, Rome, Italy) that was programmed to record a position every 1 min. Measurements of wind speed and direction using this method were similar to those observed by ship-borne ADCPs, although further quality control is needed to improve estimates of current velocity because birds are susceptible to slip at the surface depending upon wind conditions (Fossette et al., 2012; Yoda et al., 2014; Sánchez-Román et al., 2019). Miyazawa et al. (2015) showed the feasibility of assimilating high-resolution surface current data (**Figure 6**), obtained by streaked shearwaters

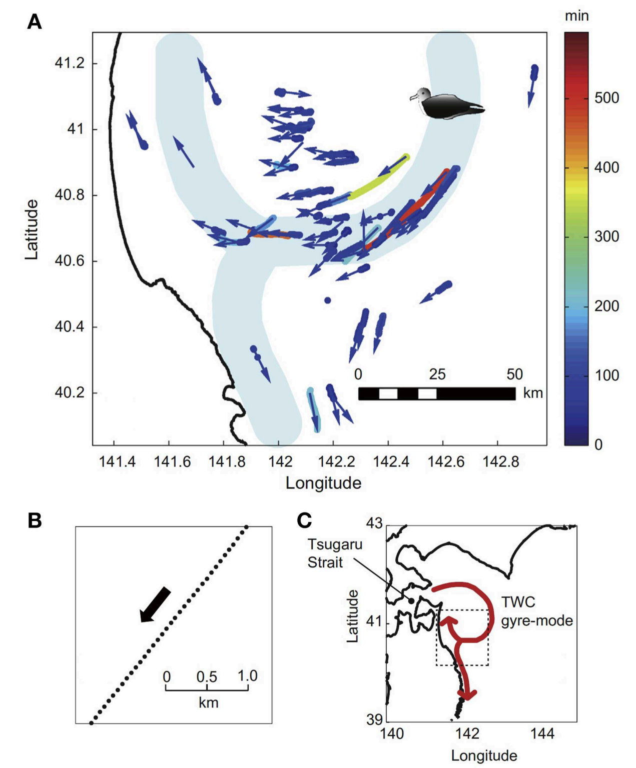

FIGURE 5 | (A) Passive drift movements of streaked shearwaters tracked in September 2010. The color bar indicates duration of drifting on seawater. Most drift tracks were shorter than 100 min, but some lasted several hours (pale blue to red tracks). The blue arrows indicate directions of drifting. **(B)** One example of drifting of a streaked shearwater. The black arrow indicates drift direction. We defined drifting as resting on water for more than 30 min with smoothness and consistency of movement direction. **(C)** The box in **(C)** is enlarged in **(A)**. The bold red line in **(C)** and the pale blue region in **(A)** are the Tsugaru Warm Current (TWC) on 10 September 2010 derived from ship-board ADCPs reported by the Marine Information Service Office, Japan Coast Guard (JCG) (URL: http://www1.kaiho.mlit.go.jp/). Reprinted from Progress in Oceanography, 122, Ken Yoda, Kozue Shiomi, Katsufumi Sato, Foraging spots of streaked shearwaters in relation to ocean surface currents as identified using their drift movements, 54-64, Copyright (2014), with permission from Elsevier.

with GPS loggers (Yoda et al., 2014) into an operational ocean forecast system during the Japan Coastal Ocean Predictability Experiment 2 (JCOPE27; see jamstec.go.jp/jcope/for real-time forecast). Furthermore, seabirds are not only passive drifters at the sea surface, they also adaptively search for prey in different prey fields (Yoda et al., 2014; Carroll et al., 2017). This feeding behavior improves the ability to monitor surface currents intensively in highly productive regions where seabirds commonly feed.

ANIMAL TELEMETRY AND ESSENTIAL OCEAN VARIABLES

Essential Ocean Variables (EOVs) are a suite of parameters that have been identified by the United Nation's Intergovernmental Oceanographic Commission's Global Ocean Observing system (GOOS) BioEco and Physics and Climate panels (Miloslavich et al., 2018). These parameters are considered crucial for the detection and attribution of change in the marine environment relevant to the global scale. Historically, GOOS has coordinated the collection of data on physical and chemical oceanographic indicators (i.e., the physical environment), and is now working to expand the monitoring to cover ecosystem and biological (EcoBio) indicators that track variation and trends in key biota and ecosystem processes (Miloslavich et al., 2018).

In addition to providing biological information about tagged individuals, animal telemetry data can provide robust, reliable, and comparable information on EcoBio EOVs. Although EcoBio EOVs are currently in development, a number of candidate variables have been proposed that relate to animal diet, phenology, and abundance (Constable et al., 2016). Foraging range is an important candidate EcoBio EOV, that is often derived from animal telemetry and can be informative about the distribution of prey and its effect on marine predators. For example, the Marine Mammals Exploring Oceans Pole-to-Pole (MEOP) program is likely to be an important source of EcoBio EOV data in the Southern Ocean (Roquet et al., 2017; Treasure et al., 2017). Parameters, such as foraging ranges, trip durations and habitat use obtained by tracking elephant seals (Mirounga sp), humpback whales (Megaptera novaeangliae), and king (Aptenodytes patagonicus), emperor (Aptenodytes forsteri), Adélie (Pygoscelis adeliae) and Gentoo (Pygoscelis papua) penguins, have been identified as a cost effective way to monitor the distribution of mesopelagic fish and krill in the ecosystem (Constable et al., 2016; Xavier et al., 2018). Because species have different habitat and dietary requirements, the species to be monitored as indicators of global ocean health need to be carefully considered.

The use of animal telemetry data for EOVs is facilitated by standardization across regional networks such as the Animal Telemetry Network (ATN, USA), Ocean Tracking Network (OTN, Canada and Global), European Telemetry Network (ETN), Acoustic Tracking Array Platform (ATAP, South Africa), and Integrated Marine Observation System Animal Tracking Facility (IMOS ATF; Australia). The adoption of common and coordinated analytical metrics (e.g., IODE OBIS; Benson et al., 2018; **Table 1**) by these regional facilities promotes the application of EOVs to global problems.

To ensure that all EOVs are relevant to Ocean Observing, GOOS has highlighted four metrics against which EOVs, including those derived from animal telemetry data, must be assessed:

- **Implementation metrics** deal with the feasibility of the approaches used to measure the EOVs and the reliability of the technology used. Land-breeding species (such as seabirds and most pinnipeds) are relatively easy to access and to instrument, ensuring regular opportunities for deployment of tracking equipment. The cost of instrumentation has declined substantially over the last decade, its reliability is high and continues to improve, analysis approaches are becoming fast and efficient, and it is now possible to instrument large samples of animals with GPS and light-level geolocation devices (Auger-Méthé et al., 2017). It is increasingly recognized that deployment of tags that are too large or too heavy can impede animal performance, compromising both the individual animal's welfare and the quality of the data that is collected (Vandenabeele et al., 2012; McIntyre, 2014). Careful selection of tags to minimize the effects on both individuals and populations prior to large scale deployments is critical. Given these caveats, though, depending on device type, tags can provide data for periods of days, weeks (high spatial resolution GPS loggers) up to a period of years currently topping out at a decade (low resolution geolocation devices, implanted acoustic tags). This means that the nature of the monitoring required will influence the choice of instrumentation.
- **Performance metrics** quantify how the observations satisfactorily represent the phenomena of interest. For example, animal tracking can address the proposed foraging range EOV, and is often the only viable tool for addressing this question, particularly during the non-breeding winter period when ship-based and aerial surveys are impractical in remote areas such as polar regions.
- **Data delivery metric**s quantify how efficiently and adequately the data from the tags are transferred to users. Some types of tracking data are available in near-real time. For example, the Argos system, when it is in contact with a tag, calculates the position of animals and provides this information to the user within 24 h. Several user groups automatically upload Argos positions for use by the broader community (e.g., IMOS). Tracking devices that rely on archived data, such as geolocation tags and some types of GPS tags, cannot deliver data until the device has been retrieved or has come within range of a base-station and the data have been downloaded. In the case of light-level geolocation, there is also a need to process the downloaded data in order to obtain position estimates. This necessarily places limits on the temporal utility of these technologies where there may be a lag of several years from deployment until the data becomes available.
- **Impact metrics** quantify use of data, information, and products for societal benefit. Examples include the number of peer-reviewed publications and research projects. The animal telemetry community has a well-established culture of publishing its work. Since the 1980s, there has been a steady increase in the number of research projects and publications from the use of marine animal telemetry (Hussey et al., 2015). In recent years there have also been increasing numbers of collaborative syntheses analyzing the many diverse data sets compiled by hundreds of individual tracking studies. These syntheses provide genuinely synergetic insights into ecological processes, such as animal foraging ranges and the factors that underpin them (Block et al., 2011; Brodie et al., 2018; Sequeira et al., 2018).

BENEFITS AND CHALLENGES OF ANIMAL TELEMETRY AS A TOOL FOR GLOBAL OCEAN OBSERVATION

Benefits for Local Conservation

Animal telemetry has immense value for aiding understanding and conservation of ocean habitats (Hays et al., 2019). At the same time as measuring animal movement, tracking devices can

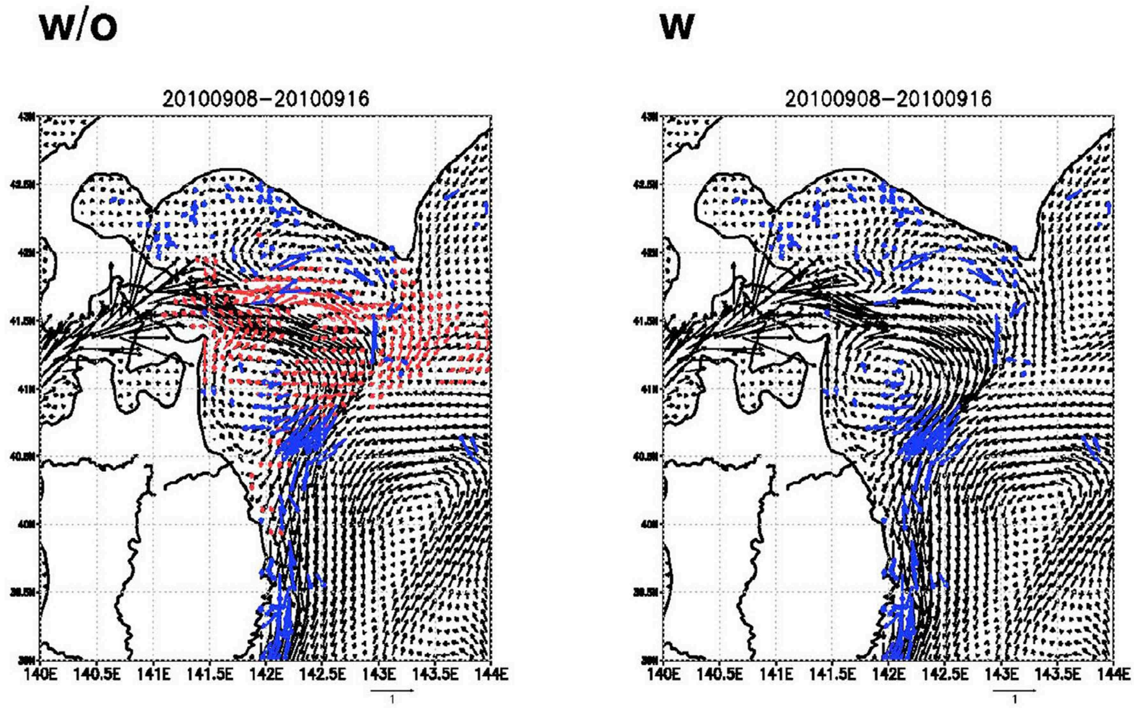

FIGURE 6 | Model current distributions at 5 m depth averaged during the target period. Left (right) panels indicate the results without (with) the assimilation of the seabird drift in the 2010 season. The composite drift data are represented by the blue colored vectors. Difference larger than 0.1 m s^{-1} in magnitude of the flows with and without the assimilation is indicated by the red colored vectors in the left panels. Numerics at the top of the figure denote the period. The figures adapted from data presented in Miyazawa et al. (2015) which is licensed under a Creative Commons Attribution 4.0 International License.

collect important observations on poorly monitored physical environments through which these animals' transit. The complex and diverse marine systems in tropical regions support a rich diversity of life including tens of marine mammal and sea turtle species, many of which are endangered. Compared to the relatively abundant data available in many other regions (e.g., Hussey et al., 2015; Sequeira et al., 2018), information about ocean use by marine fauna in tropical Asia is limited. To address these data and knowledge gaps, researchers have started data collection using available technologies. We present two examples of relatively nascent studies from tropical Asia, spanning the Pacific, and Indian Oceans to illustrate the recent application of these ideas.

In tropical Asia the green turtle (*Chelonia mydas*) is listed as Endangered (Seminoff, 2004) and the Bryde's whale (*Balaenoptera edeni*) listed as Least Concern (Cooke and Brownell, 2018) in the IUCN Red List of Threatened Species. Tropical Asia hosts more than a third of the 32 known important nesting areas (Index Sites) of green turtles, and more than half of the subpopulations nesting at these sites have been declining in the region (Seminoff, 2004). Although Bryde's whales are distributed throughout tropical Asian waters, limited population data are available and only for the upper Gulf of Thailand (Cherdsukjai et al., 2015). Satellite tracking of turtle and whale movement in the region has described space use and migration patterns, as well as having documented the need for a regional integrated effort for conservation of these megafauna. Satellite tagged green turtles at Redang Island (Liew et al., 1995), Khram Island (Chantrapornsyl et al., 2002), and Ma'Daerah Sanctuary (Van de Merwe et al., 2009), all within registered Index Sites, migrated after nesting, traveling back to their forage grounds up to 2,900 km away and spanning coastal waters of five countries. The tracked turtle routes show that the nesting population spent considerable time outside existing protected areas (e.g., no trawl zones), and hence are likely exposed to bycatch from fishing activities (Van de Merwe et al., 2009). This supports findings elsewhere, for example, recent analyses from the Mediterranean using large sample sizes showed that conservation planning that did not include turtle tracks would perform poorly, missing important habitats (Mazor et al., 2016). Similarly, satellite tracking indicated that Bryde's whales' movements in the Upper Gulf of Thailand can cover the entire Gulf (bordered by three countries) in a single week (Cherdsukjai et al., 2016). This exemplifies the need for immediate coordinated efforts in conservation planning and actions for protection of these species in this region.

The Importance of Collaboration and Data Sharing

Due to the cost and challenges associated with deploying tags and recovering data, benefits arising from the increasingly large volume of telemetry data being collected worldwide can

TABLE 1 | Summary of marine data repositories for animal-borne oceanographic sensors and observation of animal movement.

Host organization	Taxa	Regions covered	Data type	Comments
Acoustic Tracking Array Platform (ATAP; www.saiab.ac.za/atap.htm)				
South African Institute for Aquatic Biodiversity	Marine animals principally fish and sharks	Southern Africa (inshore)	Acoustic animal tracking	Launched August 2011 specifically to track the movements and migrations of inshore marine animals and make these available to the broader research community.
Atlas of Living Australia (ALA; ala.org.au)				
Commonwealth Scientific and Industrial Research Organization (CSIRO)	Australian fauna	Australia and its marine estate	Occurrence records	Launched in 2010 the Atlas aggregates biodiversity data and makes it freely available and usable online.
Animal Telemetry Network (ATN; atn.ioos.us)				
USA Integrated Ocean Observing System	Cetaceans, fish, pinnipeds, seabirds, sharks, and turtles	Pacific and Atlantic oceans including the Arctic and Antarctica	Oceanographic and climatological data and animal movement and behavior; acoustic, archival, and satellite tags	Established in 2011 to study animal movements in the world's ocean and how animals respond to changes in their physical environment.
Australian Antarctic Data Centre (AADC; data.aad.gov.au)				
Australian Government	Cetaceans, fish, pinnipeds, seabirds	Southern Ocean and Antarctica	Oceanographic and climatological data and animal movement and behavior; archival, and satellite tags	Established in 1996 to provide long-term management of Australia's Antarctic data.
Birdlife (birdlife.org.au)				
Not-for-profit private organization	Birds	Australia including its external territories and the Antarctic	Bird occurrence, distribution, and status	BirdLife Australia is a merge of Birds Australia and Bird Observation and Conservation Australia (BOCA) and has existed for more 100 years.
Census of Marine Life (http://www.coml.org/)				
See OBIS below	All marine species	Global	Diversity, distribution, and abundance of all marine species	Founded in 2000, the Census was funded by philanthropic foundations and their partners for 10 years to support a global network of researchers, investigating and explaining the diversity, distribution, and abundance of life in the oceans. Legacy projects from the Census are planned to continue into the future.
European Tracking Network (ETN; www.sextant.ifremer.fr)				
Flanders Marine Institute (VLIZ)	Cetaceans, fish, pinnipeds, seabirds, sharks, and turtles	Global	Oceanographic and climatological data and animal movement and behavior; acoustic, archival, and satellite tags	Brings together European marine researchers that use aquatic biotelemetry as a tool.
Global Seabird Tracking Database (www.seabirdtracking.org)				
Birdlife International	All seabirds	Global	Seabird movement and behavior; acoustic, archival, and satellite tag	Established in 2003 to centralize and make available seabird tracking information. Data from more than 85 species are available.
Global Shark Movement Project (www.globalsharkmovement.org)				
The Marine Biological Association	All sharks	Global	Shark movement and behavior; acoustic, archival, and satellite tags	Aims to identify movements, migrations, and habitat preferences in relation to changing ocean environment and quantify the spatial overlap between sharks and fishing vessels to inform management.
Integrated Marine Observing System (IMOS) and the Australian Ocean Data Network (AODN) (portal.aodn.org.au)				
A national collaborative research infrastructure, supported by Australian Government	Fish, fur seals, sea lions, sharks, shearwaters, Southern elephant seals, Weddell seals	Australian coast and Southern Ocean	Oceanographic and climatological data and animal movement and behavior; acoustic, archival and satellite tags	Established in 2006, IMOS operates a wide range of observing equipment, making all of its data freely accessible to the marine and climate science community, other stakeholders and users, and international collaborators.

(Continued)

TABLE 1 | Continued

Host organization	Taxa	Regions covered	Data type	Comments
Marine Mammals Exploration of the Ocean Pole to Pole (MEOP, www.meop.net)				
An international consortium of national programs	Principally marine mammals, marine turtles	Primarily the Arctic and Antarctic Oceans	Oceanographic and climatological data and animal movement and behavior.	MEOP started as an International IPY (International Polar Year) project in 2008. Since then MEOP has provided quality-controlled CTD observations to the scientific and operational oceanography communities.
Marine Megafauna Movement Analytical Program (MMMAP; mmmap.wordpress.com)				
Duke University	Marine mammals, marine turtles, seabirds	Global	Animal movement and migration routes.	Established in 2006 seeks to knowledge gaps regarding global migratory routes and connected areas.
Marine Megafauna Movement Analytical Program (MMMAP; mmmap.wordpress.com)				
University of Western Australia, Oceans Institute and the Australian Institute of Marine Science	Marine vertebrates	Global	Animal movement and behavior; acoustic, archival, and satellite tags.	Established in 2014, MMMAP brings together and international team to advance fundamental scientific knowledge of marine megafauna movement patterns and ecology.
Movebank (www.movebank.org)				
Max Planck Institute for Ornithology	All species (over 750 species to date)	Global	Principally animal movement but also includes information from other bio-logging instruments including temperature.	Established in 2007, Movebank helps researchers effectively use animal movement data and to archive these data.
Ocean Biogeographic Information system (OBIS; iobis.org)				
Intergovernmental Oceanographic Commission of UNESCO	All species	Global	Includes oceanographic and climatological data and animal movement and behavior; acoustic, archival, and satellite tags.	OBIS was born from the Oceanographic Data and Information (IODE) programme in 2009 and aims to be a comprehensive gateway to the world's ocean biodiversity and biogeographic data and information.
Ocean Tracking Network (OTN; oceantrackingnetwork.org)				
Dalhousie University, Canada	Aquatic animals	Global	Oceanographic and climatological data and animal movement and behavior; acoustic, archival, and satellite tags	OTN is responsible for the collection, aggregation, cross-referencing, and dissemination of acoustic detection data.
Pacific Ocean Shelf Tracking Project (POST; coml.org/pacific-ocean-shelf-tracking-post)				
See Census of marine Life and OBIS above	Marine animals. Cephalopods, Sturgeon and particularly salmon	Continental shelf habitats in the Pacific Ocean	Acoustic, archival, and satellite tags	POST was one of the many field research projects of the Census of Marine Life (see above) and used acoustic telemetry to track marine animals on the continental shelf of western North America. POST infrastructure and data holdings have been assimilated/expanded by the Ocean Tracking Network (see above).
Retrospective Analyses of Antarctic Tracking Data (RAATD; cesab.org/index.php/en/projets-en-cours/projets-2015/187-raatd)				
Center for Synthesis and Analysis of Biodiversity	Cetaceans, pinnipeds, seabirds	Southern Ocean and Antarctica	Animal movement and behavior; acoustic, archival and satellite tags	RAATD provides a multispecies assessment of habitat use of Antarctic meso and top predators in the Southern Ocean aiming to identify areas of ecological significance.
Sea Mammal Research Unit Instrumentation Groups (SMRU-IG; www.smru.st-and.ac.uk/Instrumentation/)				
The Sea Mammal Research Unit, University of St. Andrews	Southern elephant seals	The Southern Ocean	Oceanographic and climatological data and animal movement and behavior; archival, and satellite linked tags	An international inter-disciplinary program to increase our understanding of how southern elephant seals interact with their physical environment. Also see MEOP above.

(Continued)

TABLE 1 | Continued

Host organization	Taxa	Regions covered	Data type	Comments
seaturtle.org (www.seaturtle.org)				
Private (Michael Coyne)	Sea turtles	Global	Animal movement and behavior; archival, and satellite tags	Established in 1996, seaturtle.org is a centralized database management system to facilitate organizations working to conserve sea turtles, to manage, organize and share their data. Provides numerous online analytical tools.
Tagging of Pacific Pelagics (TOPP; www.topp.org)				
See Census of marine Life and OBIS above	Sharks, Marlin, Tuna, Turtles and northern elephant seals	The North Pacific Ocean	Oceanographic and climatological data and animal movement and behavior; acoustic, archival, and satellite linked tags	TOPP was one of the original field research projects of the global Census of Marine Life (see above).
Wildlife Computers (wildlifecomputers.com)				
Private- Wildlife Computers	Marine animals	Global	Oceanographic and climatological data and animal movement and behavior; archival and satellite tags	Established in 1984, Wildlife Computers is a provider of advanced wildlife telemetry solutions and is now also providing tools for data analyses.

be maximized if data are pooled together and can be made accessible to a broad array of researchers. Initiatives focusing on data pooling and collaborative, multidisciplinary research have created tools to greatly increase our understanding of animal movement and behavior and have led to scientific breakthroughs in the discipline of movement ecology (Hussey et al., 2015). Such breakthroughs have been made by collaborative initiatives, such as the Tagging of Pelagic Predators (TOPP; https://oceanview.pfeg.noaa.gov/topp/map), the aforementioned MEOP and IMOS ATF and the Marine Megafauna Movement Analytical Program (MMMAP; mmmap.wordpress.com), among others (**Table 1**). For example, TOPP analyzed data from 1791 individual tracks collated as part of the Census of Marine Life programme and provided a quantitative assessment of the space use, hotspots, migration pathways, and niche partitioning by multiple predator species (fish, pinnipeds, cetaceans, turtles, seabirds) in the Pacific Ocean (Costa et al., 2010b; Block et al., 2011). Data collated by IMOS-ATF led to the identification of four functional movement classes of marine animals within Australian waters based on the analysis of 2181 individuals from 92 species (including fish, sharks, and turtles; Brodie et al., 2018). The understanding of circumpolar species habitat use has been transformed by MEOP (e.g., southern elephant seals; Hindell et al., 2016). MMMAP compared global movement patterns across >2,500 individuals from 50 marine vertebrates including whales, sharks, seals, seabirds, polar bears, sirenians, and turtles, showing a remarkable convergence between movements within the coastal and open ocean (Sequeira et al., 2018).

The value of data sharing has been identified by the animal telemetry community (Nguyen et al., 2017), and the outputs from large collaborative efforts collating and analyzing tracking data are revealing that many of the key questions in animal movement (Hays et al., 2016) can only be answered through data pooling. To assist the development of such studies, a select group of credible online data repositories is now emerging (**Table 1**; Campbell et al., 2016). These include, for example, OTN, BirdLife International (2012) and Movebank (Wikelski and Kays, 2010). Collectively, such repositories are globally accessible, strive to use open source software and common (or at least easily mappable) formats, and amass and curate large quantities of movement data and metadata across thousands of species extending across most regions of the globe (Hussey et al., 2015; Kays et al., 2015). Analysis of the large spatial and temporal datasets now available will allow establishment of baselines from which large-scale (1000s km) and long-term (decadal) changes can be identified, which in turn will provide conservation benefits through informed planning and management (Allen and Singh, 2016; Fraser et al., 2018), and will "*increase global communication, scope for collaboration, intellectual advancement, and funding opportunities*" (Hussey et al., 2015).

Pooling datasets collected in disparate ways with different instruments, or secondarily derived from other primary data (e.g., model simulation outputs), will, however, bring new analytical challenges. A potential way to address some of these challenges is through multi-disciplinary approaches, promoting the engagement of researchers from disparate fields, including ecologists, physiologists, physicists, mathematicians, and computer and visualization scientists. A combination of existing and new analytical techniques will most likely be required to realize the full potential of the large amount of telemetry data now in existence (Hussey et al., 2015) and facilitate the use of big data approaches to significantly enhance our understanding of animal movement (Hampton et al., 2013; Meekan et al., 2017; Rodríguez et al., 2017; Thums et al., 2018).

For studies that integrate observations from telemetry data into oceanographic observing, there are clear mutual benefits of collaboration between ecologists who generally deploy tags, and oceanographers who are also end-users of the data. The need for international coordination of deployment of animal-borne sensors to address data coverage gaps was recognized more than 15 years ago, in particular the challenge of coordinating resources to enable simultaneous deployments across several sub-Antarctic sites. To address this, the project SEaOS (Southern Elephant seals as Oceanographic Samplers) was launched in 2003 with participants from five national groups. This led to the MEOP program that began during the International Polar Year period in 2008–2009.

MEOP has now transformed into a large consortium that acts to bridge the scientific teams deploying the tags and those using the data (Treasure et al., 2017). The MEOP data (**Figure 3**) are made available to the global scientific community through the data portal (http://www.meop.net). Similar efforts are underway within other components of the global animal telemetry and oceanographic community, including the US Animal Telemetry Network (https://atn.ioos.us /, Block et al., 2016), the EuroGOOS Animal-Borne Instrument (ABI) Task Team in Europe, the Integrated Marine Observing System (through its Animal Tracking Facility (IMOS ATF; imos.org.au), the Canadian Ocean Tracking Network (oceantrackingnetwork.org/), and the framework provided by the Observations Coordination Group of the Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM-OCG; **Table 1**). Future success in integrating data from animal-borne instruments into ocean observing systems will depend on three key requirements: sufficient data quality, data standardization and robust data delivery.

Challenges of Incorporating Data From Animal-Borne Platforms Into Operational Oceanography Systems

Despite the successes of international and cross-disciplinary collaboration between ecologists and oceanographers, hydrographic information collected from animal-borne platforms have too rarely been used routinely for operational oceanography. A primary reason for this has been the difficulty to obtain dedicated resources in ocean data centers for the processing of animal data, encompassing the registration of the individual tags (also known as "platforms"), the data processing and the subsequent uptake of their data through the Global Telecommunication System (GTS) to, among others, the climate operations community. For example, data from CTD-SRDLs are directly managed by the instrument manufacturer (SMRU, University of St. Andrews), where the data are decoded and the profiles rebuilt before distribution through the British Oceanographic Data Center (BODC). At the BODC, the data are then automatically converted into either TESAC or BUFR formats and sent to the GTS for operational use. However, in contrast to what is done for Argo float data, BODC has to date no dedicated resources to quality control and flag the animal data before transmission to the GTS, limiting importantly the usability of the data for data assimilation.

The complexity of encoding, decoding, and transmitting these data and posting them on the GTS is in part the result of unavoidable constraints imposed by both the animals' behavior, the small size of the tags and the CLS Argos data transmission system. Tags on animals must be as small as possible so as to not adversely affect the animal; therefore, the energy available to the tags is extremely limited. The animals themselves further constrain the way data is processed and sent because of their behavior, largely because they vary their diving and surfacing behavior in an unpredictable way, only returning to the surface infrequently for brief periods which imposes further bandwidth limitations (see Photopoulou et al., 2015 for details). Data received from the tags may be transmitted hours or even days after their collection, further delaying data reception and data delivery. This is because the data is buffered for transmission and the success rates of transmission depend on how long the animal stays at the surface and the availability of satellites at the time of surfacing. Taken together, these complexities mean that real time processing and data dissemination may not be as straightforward to implement as that from the more predictable data stream from Argo floats.

An important component of data uptake, use and integration is access to the individual platform metadata. Currently animal metadata are not centralized or easily accessed and given that the Joint Technical Commission for Oceanography (JCOMMs) *in situ* Observing Programmes Support Center (JCOMMOPS) already manages platform metadata for gliders, Argo float and sensors on ships, it follows that as part of the broader and globally comprehensive ocean observing system, the physical environment data from animal-borne tags could also be managed by JCOMMOPS. The basic metadata associated with the observations would ideally include: World Meteorological Organization (WMO) identifying numbers, the principal investigator's name, species name, sensor information from the manufacturer, tag program configurations, sensor calibration, diagnostics and data adjustment coefficients and the quality control details and quality flags. Additional effort on the part of projects deploying the animal tags is needed to improve metadata availability.

Recent Technological Advances and Future Directions

Developments in Telemetry Technology

In the decade since OceanObs 09, the application of animal telemetry has provided significant amounts of data from otherwise difficult to sample situations. Furthermore, ocean observing using animal-borne platforms has demonstrated the importance of animal telemetry data to a broader understanding of ocean processes (Roquet et al., 2013). Thus, improvements in accuracy and reliability as well as expanding the range of sensors on animal tags is clearly important as is broadening applicability more and varied species. Developments include new, small, low-power sensors that sample additional parameters capable at extremely low duty cycles to allow for continuous monitoring of animals. Sensors for fluorescence (Guinet et al., 2013), oxygen (Bailleul et al., 2015), light levels (Teo et al., 2004), sound (Cazau et al., 2017), acceleration (Carroll et al., 2014, 2016; Cox et al., 2018), and active sonar (Lawson et al., 2015) have all been deployed (**Figure 1**) but most require refinement. Each of these contribute to a better understanding of the link between physical, biogeochemical, and ecological processes.

Revolutions in sensor technology are also being translated into a new generation of sensors to track marine life, with significantly reduced footprints and power requirements, including the capacity to harvest power from the environment, better accommodating animal anatomy and movement and containing significantly enhanced capacities for data storage and analysis. Examples of these revolutionary sensors include the "*marine skin,*" a flexible-stretchable silicon-printed sensor system that brings the concept of wearable to marine animal tags (Nassar et al., 2018), new magnetic sensors to monitor animal behaviors in detail (Kaidarova et al., 2018a), and graphene-based flexible, ultrathin, and light salinity sensors to acquire oceanographic information (Kaidarova et al., 2018b).

Improved Metadata Standardization

For data systems, community-wide data standards for the exchange of tracking data are well advanced (e.g., Benson et al., 2018; IODE OBIS Event Data workshop on Animal Tagging Tracking F. w., 2018), but not yet universally accepted. The development of coordinated systems that provide information on animal movements and distributions globally, in (near) real-time, are a necessity given the rapid expansion in the use of the technology and would be a strong asset for GOOS. Globally, there are already a number of extant but independently evolved web-based platforms for the management and analysis of animal movement data (**Table 1**). Collating data into these repositories provides internal standardization and accessibility. For example, Zoatrack is hosted on the Atlas of Living Australia and has a relational data model based on animal identifiers, timestamps and locations, for satellite or GPS based movement data that are provided via direct file uploads or automated feed from the Argos satellite network (Dwyer et al., 2015). It also has a spatial interface where environmental spatial layers can be added, and data can be discovered by species or location. The Atlas of Living Australia typically ingests data in Simple Darwin Core, a flat file format, which accommodates simple occurrence data well (Newman et al., 2018). ZoaTrack records are summarized into this format by representing a track as an occurrence record with a summary footprint over a date range.

An implementation like this as a metadata catalog allows tracking data to be discoverable and begins opening possibilities for API development and machine interoperability between other external systems and users. However, there will be challenges in accomplishing the latter as data fields and vocabularies vary among the different systems due to their independent evolution. Recently, a roadmap indicating a positive way to negotiate these inconsistencies has been proposed (Sequeira et al., under review). It will also be important to ensure that data are not available to individuals or organizations who could use it to exploit or otherwise disturb or harass tagged wildlife or their untagged conspecifics (Cooke et al., 2017), and new frameworks are being developed to address these sensitive issues (Lennox et al., under review).

A Step Change in Analysis—Big Data

Challenges are arising for analysis of the dramatically increasing amount of acoustic and satellite tracking data. The telemetry field is growing in a similar way to other fields of research where "big data" analyses are now commonplace (e.g., human mobility, Meekan et al., 2017). For animal telemetry, this starts with finding approaches to permit faster and more efficient computing and model fitting (e.g., Whoriskey et al., 2017; Jonsen et al., 2018). The fields of Statistical Physics and Complex Systems have been developing and applying techniques that deal with big data of movement. These techniques have developed from classical work focused on single trajectories and how analyzing collective movements (e.g., Vicsek and Zafeiris, 2012; Morin et al., 2017) can improve an understanding of search strategies and their properties (e.g., Benichou et al., 2011). Collective movement has also been studied using network-based techniques, either focusing on animal social networks (e.g., Krause et al., 2013; Daniels et al., 2017) and leadership (e.g., Jacoby et al., 2016; Mwaffo et al., 2018), detecting patterns and drivers of movement across multiple individuals (e.g., Abrahms et al., 2017; Rodríguez et al., 2017), or by trying to understand communication and transmission of culture (e.g., Carroll et al., 2015; Sasaki and Biro, 2017). Advances made using such approaches are generating new insights about animal movements and their drivers (Rodríguez et al., 2017). The real-time nature of marine animal telemetry can also be used to inform real-time management actions, such as interventions with ship traffic to avoid collisions between marine animals and vessels, and warning beach goers of risk of shark presence (Hazen et al., 2017; Pirotta et al., 2019). This requires real-time integration and analyses of massive amounts of data, something only possible with the assistance of machine learning tools.

ANIMAL TRACKING AS AN OCEAN OBSERVING TOOL 2019–2029

The advancement of human technologies has made the ocean the next great frontier for industrial development (McCauley et al., 2015; Ogburn et al., 2017; World Economic Forum, 2017). For this "Blue Growth" agenda to be sustainable, and to ensure that rapidly expanding marine developments do not compromise the existing socioeconomic benefits and essential ecosystem services humanity derives from the ocean, managers and policy makers need to be informed by comprehensive monitoring of the ocean. Animal telemetry has a crucial role to play in this task. The species selected for tracking are typically of high value either because of their role in the human food supply or because of the roles they play in ecosystems (Cooke, 2008; Fraser et al., 2018). Many of these animals move on scales ranging from local (a few meters to tens of kms) to entire ocean basins (thousands of kms), in order to meet their needs.

Identifying the pathways that they follow and the habitats they use is important for informed management and implementing effective conservation actions. Telemetry is an ideal tool to provide this information. Meanwhile, environmental conditions in the ocean are changing in ways not completely understood, driven largely by anthropogenic climate forcing among other causes. Animal habitats and movement pathways will change with these environmental characteristics, as will the environmental services the ocean provides, and the risks posed to people who live and work on the ocean. Greater and better observations of the physical environment are required to manage these risks, on a scale comparable with what has been achieved for terrestrial weather forecasting. Enlisting "animal oceanographers" cost-effectively provides relevant information in areas that are difficult to reach and need to be sampled. Sensor technology is rapidly evolving, and the creation of new, miniaturized sensors and data flows will allow scientists to address emerging issues, such as ocean acidification. However, the large amount of data to be generated through these technological improvements will need a refocus of attention and resources directed toward the challenge of storing, curating, analyzing, and communicating the knowledge, stemming from our greatly expanded observations.

Observations obtained through animal telemetry now span oceanography and physics through to ecology and animal physiology and provide critical information for detecting and attributing change in the marine environment. The high quality of the data and its temporal and spatial breadth is critical to GOOS and forms the basis of the proposed new EcoBio EOVs. Technological advances and the recent exponential growth of animal telemetry enabling the sampling of a wide range of environments (ranging from coastal to open oceans and from tropical to polar regions) has made observations from animal borne tags a mature contributor to ocean observation.

AUTHOR CONTRIBUTIONS

RH, AS, FR, KKo, XZ, and MF: conception, core authorship, senior editing and writing. MHe, CS, CM, FW, MMe, GC, SB, MHi, and IJ: editing and written contribution. DPC, BB, MMu, BW, MW, KA, MB, LB, SJB, DC, J-BC, SJC, PC, PJNdB, TJ, CD, VE, LF, JF-G, KG, YG, CG, MHa, GH, EH, LH, CH, SI, SJ, KKi, KMK, CL, TM, MN, LP, BP, NQ, GR, KS, DWS, ET, MT, AMT, AWT, GW, and YY: written contribution.

REFERENCES

Aarestrup, K., Økland, F., Hansen, M. M., Righton, D., Gargan, P., Castonguay, M., et al. (2009). Oceanic spawning migration of the European eel (Anguilla anguilla). *Science* 325, 1660–1660. doi: 10.1126/science.1178120

Aarts, G., MacKenzie, M., McConnell, B., Fedak, M., and Matthiopoulos, J. (2008). Estimating space-use and habitat preference from wildlife telemetry data. *Ecography* 31, 140–160. doi: 10.1111/j.2007.0906-7590.05236.x

Abrahms, B., Seidel, D. P., Dougherty, E., Hazen, E. L., Bograd, S. J., Wilson, A. M., et al. (2017). Suite of simple metrics reveals common movement syndromes across vertebrate taxa. *Mov. Ecol.* 5:2. doi: 10.1186/s40462-017-0104-2

Albert, A., Echevin, V., Lévy, M., and Aumont, O. (2010). Impact of nearshore wind stress curl on coastal circulation and primary productivity in the Peru upwelling system. *J. Geophys. Res.* 115:C12033. doi: 10.1029/2010JC006569

Allen, A. M., and Singh, N. J. (2016). Linking movement ecology with wildlife management and conservation. *Front. Ecol. Evol.* 3:155. doi: 10.3389/fevo.2015.00155

Arthun, M., Nicholls, K. W., Makinson, K., Fedak, M. A., and Boehme, L. (2012). Seasonal inflow of warm water onto the southern Weddell Sea continental shelf, Antarctica. *Geophys. Res. Lett.* 39:L17601. doi: 10.1029/2012GL052856

Auger-Méthé, M., Albertsen, C. M., Jonsen, I. D., Derocher, A. E., Lidgard, D. C., Studholme, K. R., et al. (2017). Spatiotemporal modelling of marine movement data using Template Model Builder (TMB). *Mar. Ecol. Prog. Ser.* 565, 237–249. doi: 10.3354/meps12019

Avgar, T., Potts, J. R., Lewis M. A., and Boyce, M. S. (2016). Integrated step selection analysis: bridging the gap between resource selection and animal movement. *Methods Ecol. Evol.* 7, 619–630. doi: 10.1111/2041-210X.12528

Bailey, J. D., Wallis, J., and Codling, E. A. (2018). Navigational efficiency in a biased and correlated random walk model of individual animal movement. *Ecology* 99, 217–223. doi: 10.1002/ecy.2076

Bailleul, F., Vacquie-Garcia, J., and Guinet, C. (2015). Dissolved oxygen sensor in animal-borne instruments: an innovation for monitoring the health of oceans and investigating the functioning of marine ecosystems. *PLoS ONE* 10:e0132681. doi: 10.1371/journal.pone.0132681

Barton, K. A., Phillips, B. L., Morales, J. M., and Travis, J. M. J. (2009). The evolution of an 'intelligent' dispersal strategy: biased, correlated random walks in patchy landscapes. *Oikos* 118, 309–319. doi: 10.1111/j.1600-0706.2008.16936.x

Bastille-Rousseau, G., Potts, J. R., Schaefer, J. A., Lewis, M. A., Ellington, E. H., Rayl, N. D., et al. (2015). Unveiling trade-offs in resource selection of migratory caribou using a mechanistic movement model of availability. *Ecography* 38, 1049–1059. doi: 10.1111/ecog.01305

Benichou, O., Loverdo, C., Moreau, M., and Voituriez, R. (2011). Intermittent search strategies. *Rev. Modern Phys.* 83:81. doi: 10.1103/RevModPhys.83.81

Benson, A., Appeltans, W., Bajona, L., Bosch, S., Cowley, P., De Pooter, D., et al. (2018). Outcomes of the international oceanographic data and information exchange ocean biogeographic information system OBIS-event-data workshop on animal tagging and tracking. *Biodivers. Inform. Sci. Standards* 2:e25728. doi: 10.3897/biss.2.25728

Bestley, S., Jonsen, I. D., Hindell, M. A., Guinet, C., and Charrassin, J. B. (2013). Integrative modelling of animal movement: incorporating *in situ* habitat and behavioural information for a migratory marine predator. *Proc. R. Soc. Biol. Sci.* 280:20122262. doi: 10.1098/rspb.2012.2262

BirdLife International (2012). *Tracking Devices Provide New Insights Into Seabird Migration*. Available online at: http://www.birdlife.org on 07/11/2018

Biuw, M., Boehme, L., Guinet, C., Hindell, M., Costa, D., Charrassin, J. B., et al. (2007). Variations in behavior and condition of a Southern Ocean top predator in relation to *in situ* oceanographic conditions. *Proc. Natl. Acad. Sci.* 104, 13705–13710. doi: 10.1073/pnas.0701121104

Block, B. A. (2005). Physiological ecology in the 21st century: advancements in biologging science. *Integr. Compar. Biol.* 45, 305–320. doi: 10.1093/icb/45.2.305

Block, B. A., Dewar, H., Farwell, C., and Prince, E. D. (1998). A new satellite technology for tracking the movements of Atlantic bluefin tuna. *Proc. Natl. Acad. Sci.* 95, 9384–9389. doi: 10.1073/pnas.95.16.9384

Block, B. A., Holbrook, C. M., Simmons, S. E., Holland, K. N., Ault, J. S., Costa, D. P., et al. (2016). Toward a national animal telemetry network for aquatic observations in the United States. *Anim. Biotelemetry* 4:6. doi: 10.1186/s40317-015-0092-1

Block, B. A., Jonsen, D. I., Jorgensen, S. J., Winship, A. J., Shaffer, S. A., Bograd, S. J., et al. (2011). Tracking apex marine predator movements in a dynamic ocean. *Nature* 475, 86–90. doi: 10.1038/nature10082

Boehlert, G. W., Costa, D. P., Crocker, D. E., Green, P., O'Brien, T., Levitus, S., et al. (2001). Autonomous pinniped environmental samplers: using instrumented animals as oceanographic data collectors. *J. Atmos. Oceanic Technol.* 18, 1882–1893. doi: 10.1175/1520-0426(2001)018andlt;1882:APESUIandgt;2.0.CO;2

Boehme, L., Lovell, P., Biuw, M., Roquet, F., Nicholson, J., Thorpe, S. E., et al. (2009). Technical note: animal-borne CTD-Satellite Relay Data Loggers for real-time oceanographic data collection. *Ocean Sci.* 5, 685–695. doi: 10.5194/os-5-685-2009

Boehme, L., Meredith, M., Thorpe, S., Biuw, M., and Fedak, M. A. (2008). C9.The ACC frontal system in the South Atlantic: monitoring using merged Argo and animal-borne sensor data. *J. Geophys. Res.* 113:C9. doi: 10.1029/2007JC004647

Bograd, S. J., Block, B. A., Costa, D. P., and Godley, B. J. (2010). Biologging technologies: new tools for conservation. *Introduction Endangered Species Res.* 10, 1–7. doi: 10.3354/esr00269

Brodie, S., Lédée, E. J. I., Heupel, M. R., Babcock, R. C., Campbell, H. A., Gledhill, D. C., et al. (2018). Continental-scale animal tracking reveals functional movement classes across marine taxa. *Sci. Rep.* 8:5. doi: 10.1038/s41598-018-21988-5

Campbell, H. A., Urbano, F., Davidson, S., Dettki, H., and Cagnacci, F. (2016). A plea for standards in reporting data collected by animal-borne electronic devices. *Anim. Biotelemetry* 4:96. doi: 10.1186/s40317-015-0096-x

Carroll, E. L., Baker, C. S., Watson, M., Alderman, R., Bannister, J., Gaggiotti, O. E., et al. (2015). Cultural traditions across a migratory network shape the genetic structure of southern right whales around Australia and New Zealand. *Sci. Rep.* 5:16182. doi: 10.1038/srep16182

Carroll, G., Cox, M., Harcourt, R., Pitcher, B., Slip, D., and Jonsen, I. (2017). Hierarchical influences of prey distribution on patterns of prey capture by a marine predator. *Funct. Ecol.* 31, 1750–1760. doi: 10.1111/1365-2435.12873

Carroll, G., Everett, J. D., Harcourt, R., Slip, D., and Jonsen, I. (2016). High sea surface temperatures driven by a strengthening current reduce foraging success by penguins. *Sci. Rep.* 6:22236. doi: 10.1038/srep22236

Carroll, G., Slip, D., Jonsen, I., and Harcourt, R. (2014). Supervised accelerometry analysis can identify prey capture by penguins at sea. *J. Exp. Biol.* 217, 4295–4302. doi: 10.1242/jeb.113076

Cazau, D., Bonnel, J., Jouma'a, J., Le Bras, Y., and Guinet, C. (2017). Measuring the marine soundscape of the Indian Ocean with southern elephant seals used as acoustic gliders of opportunity. *J. Atmos. Oceanic Technol.* 34, 207–223. doi: 10.1175/JTECH-D-16-0124.1

Chantrapornsyl, S., Charuchinda, M., Sakamoto, W., Arai, N., Klom-In, W., Kittiwattanawong, K., et al. (2002). *Migration Tracking of Green Turtles (Chelonia mydas) Using Platform Transmitter Terminals*. Available online at: https://www.dmcr.go.th/upload/dt/file/file-612-966145833.pdf

Charrassin, J. B., Hindell, M., Rintoul, S. R., Roquet, F., Sokolov, S., Biuw, M., et al. (2008). Southern Ocean frontal structure and sea-ice formation rates revealed by elephant seals. *Proc. Natl. Acad. Sci.* 105, 11634–11639. doi: 10.1073/pnas.0800790105

Cherdsukjai, P., Thongsukdee, S., Passada, S., and Prempree, T. (2015). Population sizes of Bryde's whale (Balaenoptera edeni) in the Upper Gulf of Thailand, estimated by mark and recapture method. *Proc. Des. Symp. Conser. Ecosystem* 3. doi: 10.14989/198821

Cherdsukjai, P., Thongsukdee, S., Passada, S., Prempree, T., and Yaovasuta, P. (2016). "Satellite tracking of Bryde's whale (*Balaenoptera edeni*), in the Upper Gulf of Thailand," in *Proceedings of 5th Marine Science Conference. 1-3 June 2016*, Bangkok. 104–114.

Cherry, S. G., Derocher, A. E., Thiemann, G. W., and Lunn, N. J. (2013). Migration phenology and seasonal fidelity of an Arctic marine predator in relation to sea ice dynamics. *J. Anim. Ecol.* 82, 912–921. doi: 10.1111/1365-2656.12050

Constable, A. J., Costa, D. P., Schofield, O., Newman, L., Urban, E. R., Fulton, E. A., et al. (2016). Developing priority variables ("ecosystem Essential Ocean Variables" - eEOVs) for observing dynamics and change in Southern Ocean ecosystems. *J. Mar. Syst.* 161, 26–41. doi: 10.1016/j.jmarsys.2016.05.003

Cooke, J. G., and Brownell, R. L. Jr. (2018). *Balaenoptera edeni*. The IUCN Red List of Threatened Species 2018:e.T2476A50349178.

Cooke, S. J. (2008). Biotelemetry and biologging in endangered species research and animal conservation: relevance to regional, national, and IUCN Red List threat assessments. *Endangered Species Res.* 4, 165–185. doi: 10.3354/esr00063

Cooke, S. J., Nguyen, V. M., Kessel, S. T., Hussey, N., Young, N., and Ford, A. T. (2017). Troubling and unanticipated issues at the frontier of animal tracking for conservation and management. *Conserv. Biol.* 31, 1205–1207. doi: 10.1111/cobi.12895

Costa, D. P., Block, B. A., Bograd, S., Fedak, M. A., and Gunn, J. S. (2010a). TOPP as a marine life observatory: using electronic tags to monitor the movements, behaviour and habitats of marine vertebrates. *Proc. OceanObs* 9, 21–25. doi: 10.5270/OceanObs09.cwp.19

Costa, D. P., Breed, G. A., and Robinson, P. W. (2012). New insights into pelagic migrations: implications for ecology and conservation. *Ann. Rev. Ecol. Evol. Syst.* 43, 73–96. doi: 10.1146/annurev-ecolsys-102710-145045

Costa, D. P., Huckstadt, L. A., Crocker, D. E., McDonald, B. I., Goebel, M. E., and Fedak, M. A. (2010b). Approaches to studying climatic change and its role on the habitat selection of antarctic pinnipeds. *Integr. Comput. Biol.* 50, 1018–1030. doi: 10.1093/icb/icq054

Costa, D. P., Klinck, J., Hofmann, E. E., Dinniman, M., and Burns, J. M. (2008). Upper ocean variability in west Antarctic Peninsula continental shelf waters as measured using instrumented seals. *Deep Sea Res.* 55, 323–337. doi: 10.1016/j.dsr2.2007.11.003

Cox, S. L., Orgeret, F., Gesta, M., Rodde, C., Heizer, I., Weimerskirch, H., et al. (2018). Processing of acceleration and dive data on-board satellite relay tags to investigate diving and foraging behaviour in free-ranging marine predators. *Methods Ecol. Evol.* 9, 64–77. doi: 10.1111/2041-210X.12845

Daniels, B. C., Krakauer, D. C., and Flack, J. C. (2017). Control of finite critical behaviour in a small-scale social system. *Nat. Commun.* 8:14301. doi: 10.1038/ncomms14301

Donaldson, M. R., Hinch, S. G., Suski, C. D., Fisk, A. T., Heupel, M. R., and Cooke, S. J. (2014). Making connections in aquatic ecosystems with acoustic telemetry monitoring. *Front. Ecol. Environ.* 12, 565–573. doi: 10.1890/130283

Dwyer, R. G., Brooking, C., Brimblecombe, W., Campbell, H. A., Hunter, J., Watts, M., et al. (2015). An open web-based system for the analysis and sharing and analysis of animal tracking data. *Anim. Biotelemetry* 3:8. doi: 10.1186/s40317-014-0021-8

Everett, A., Kohler, J., Sundfjord, A., Kovacs, K. M., Torsvik, T., Pramanik, A., et al. (2018). Subglacial discharge plume behaviour revealed by CTD-instrumented ringed seals. *Sci. Rep.* 8:13467. doi: 10.1038/s41598-018-31875-8

Fedak, M., Lovell, P., McConnell, B., and Hunter, C. (2002). Overcoming the constraints of long range radio telemetry from animals: getting more useful data from smaller packages. *Integr. Compar. Biol.* 42, 3–10. doi: 10.1093/icb/42.1.3

Fedak, M. A. (2004). Marine animals as platforms for oceanographic sampling: a "win/win" situation for biology and operational oceanography. *Memoirs Natl. Institute Polar Res.* 58, 133–147.

Fedak, M. A. (2013). The impact of animal platforms on polar ocean observation. *Deep Sea Res.* 88, 7–13. doi: 10.1016/j.dsr2.2012.07.007

Fossette, S., Putman, N. F., Lohmann, K. J., Marsh, R., Hays, G. C. (2012). A biologist's guide to assessing ocean currents: a review. *Mar. Ecol. Prog. Ser.* 457, 285–301. doi: 10.3354/meps09581

Fraser, K. C., Davies, K. T. A., Davy, C. M., Ford, A. T., Tyler Flockhard, D. T., and Martins, G. C. (2018). Tracking the conservation promise of movement ecology. *Front. Ecol. Evol.* 6:150. doi: 10.3389/fevo.2018.00150

Frazer, E. K., Langhorne, P. J., Williams, M. J. M., Goetz, K. T., and Costa, D. P. (2018). A method for correcting seal-borne oceanographic data and application to the estimation of regional sea ice thickness. *J. Mar. Syst.* 187, 250–259. doi: 10.1016/j.jmarsys.2018.08.002

Goetz, K. T. (2015). *Movement, Habitat, and Foraging Behavior of Weddell Seals (Leptonychotes weddellii) In the Western Ross Sea, Antarctica*. Dissertation. University of California, Santa Cruz, CA.

Goto, Y., Yoda, K., and Sato, K. (2017). Asymmetry hidden in birds' tracks reveals wind, heading, and orientation ability over the ocean. *Sci. Adv.* 3:e1700097. doi: 10.1126/sciadv.1700097

Griffin, L. P., Brownscombe, J. W., Adams, A. J., Boucek, R. E., Finn, J. T., Heithaus, M. R., et al. (2018). Keeping up with the Silver King: using cooperative acoustic telemetry networks to quantify the movements of Atlantic tarpon (*Megalops atlanticus*) in the coastal waters of the southeastern United States. *Fish. Res.* 205, 65–76. doi: 10.1016/j.fishres.2018.04.008

Grist, J. P., Josey, S. A., Boehme, L., Meredith, M. P., Davidson, F. J. M., Stenson, G. B., et al. (2011). Temperature signature of high latitude Atlantic boundary currents revealed by marine mammal-borne sensor and Argo data. *Geophys. Res. Lett.* 38:15. doi: 10.1029/2011GL048204

Guinet, C., Xing, X., Walker, E., Monestiez, P., Marchand, S., Picard, B., et al. (2013). Calibration procedures and first data set of Southern Ocean chlorophyll a profiles collected by elephant seals equipped with a newly developed CTD-fluorescence tags. *Earth Syst. Sci. Data* 5, 15–29. doi: 10.5194/essd-5-15-2013

Hampton, S. E., Strasser, C. A., Tewksbury, J. J., Gram, W. K., Budden, A. E., Batcheller, A. L., et al. (2013). Big data and the future of ecology. *Front. Ecol. Environ.* 11, 156–162. doi: 10.1890/120103

Hawkes, L. A., Broderick, A. C., Godfrey, M. H., and Godley, B. J. (2009). Climate change and marine turtles. *Endangered Species Res.* 7, 137–154. doi: 10.3354/esr00198

Hays, G. C., Bailey, H., Bograd, S. J., Bowen, W. D., Campagna, C., Carmichael, R. H., et al. (2019). Translating marine animal tracking data into conservation policy and management. *Trends Ecol. Evol.* 34, 385-486, e1–e2. doi: 10.1016/j.tree.2019.01.009

Hays, G. C., Ferreira, L. C., Sequeira, A. M. M., Meekan, M. G., Duarte, C. M., Bailey, H., et al. (2016). Key questions in marine megafauna movement ecology. *Trends Ecol. Evol.* 31, 463–475. doi: 10.1016/j.tree.2016.02.015

Hays, G. C., Hobson, V. J., Metcalfe, J. D., Righton, D., and Sims, D. W. (2006). Flexible foraging movements of leatherback turtles across the North Atlantic Ocean. *Ecology* 87, 2647–2656. doi: 10.1890/0012-9658(2006)87[2647:FFMOLT]2.0.CO;2

Hazen, E. L., Abrahms, B., Brodie, S., Carroll, G., Jacox, M. G., Savoca, M. S., et al. (2019). Marine top predators as climate and ecosystem sentinels. *Front. Ecol. Environ*. (accepted)

Hazen, E. L., Jorgensen, S., Rykaczewski, R. R., Bograd, S. J., Foley, D. G., Jonsen, I. D., et al. (2013b). Predicted habitat shifts of Pacific top predators in a changing climate. *Nat. Climate Change* 3:234. doi: 10.1038/nclimate1686

Hazen, E. L., Maxwell, S. M., Bailey, H., Bograd, S. J., Hamann, M., Gaspar, P., et al. (2013a). Ontogeny in marine tagging and tracking science: technologies and data gaps. *Mar. Ecol. Prog. Ser.* 457, 221–240. doi: 10.3354/meps09857

Hazen, E. L., Palacios, D. M., Forney, K. A., Howell, E. A., Becker, E., Hoover, A. L., et al. (2017). WhaleWatch: a dynamic management tool for predicting blue whale density in the California Current. *J. Appl. Ecol.* 54, 1415–1428. doi: 10.1111/1365-2664.12820

He, R., Liu, Y., and Weisberg, R. H. (2004). Coastal ocean wind fields gauged against the performance of an ocean circulation model. *Geophys. Res. Lett.* 31:L14303. doi: 10.1029/2003GL019261

Heupel, M. R., Semmens, J. M., and Hobday, A. J. (2006). Automated acoustic tracking of aquatic animals: scales, design and deployment of listening station arrays. *Mar. Freshw. Res.* 57, 1–13. doi: 10.1071/MF05091

Hindell, M. A., McMahon, C. R., Bester, M. N., Boehme, L., Costa, D., Fedak, M. A., et al. (2016). Circumpolar habitat use in the southern elephant seal: implications for foraging success and population trajectories. *Ecosphere* 7:e01213. doi: 10.1002/ecs2.1213

Hoenner, X., Huveneers, C., Steckenreuter, A., Simpfendorfer, C., Tattersall, K., Jaine, F., et al. (2018). Australia's continental-scale acoustic tracking database and its automated quality control process. *Sci. Data* 5:206. doi: 10.1038/sdata.2017.206

Humphries, N. E., Queiroz, N., Dyer, J. R., Pade, N. G., Musyl, M. K., Schaefer, K. M., et al. (2010). Environmental context explains Lévy and Brownian movement patterns of marine predators. *Nature* 465, 1066–1069. doi: 10.1038/nature09116

Hussey, N. E., Kessel, S. T., Aarestrup, K., Cooke, S. J., Cowley, P. D., Fisk, A. T., et al. (2015). Aquatic animal telemetry: a panoramic window into the underwater world. *Science* 348, 1221–1231. doi: 10.1126/science.1255642

IODE OBIS Event Data workshop on Animal Tagging and Tracking F. w. (2018). *Reports of Meetings of Experts and Equivalent Bodies*.

Isachsen, P. E., Sørlie, S. R., Mauritzen, C., Lydersen, C., Dodd, P., and Kovacs, K. M. (2014). Upper-ocean hydrography of the Nordic Seas during the International Polar Year (2007–2008) as observed by instrumented seals and Argo floats. *Deep Sea Res. I* 93, 41–59. doi: 10.1016/j.dsr.2014.06.012

Jacoby, D. M., Papastamatiou, Y. P., and Freeman, R. (2016). Inferring animal social networks and leadership: applications for passive monitoring arrays. *J. R. Soc. Interface* 13:676. doi: 10.1098/rsif.2016.0676

Johnson, D. S., London, J. M., Lea, M. A., and Durban, J. W. (2008). Continuous-time correlated random walk model for animal telemetry data. *Ecology* 89, 1208–1215. doi: 10.1890/07-1032.1

Jonsen, I., McMahon, C., Patterson, T., Auger-Methe, M., Harcourt, R., Hindell, M., et al. (2018). Movement behaviour responses to environment: fast inference of individual variation with a mixed effects model. *Ecology* 100:e02566. doi: 10.1002/ecy.2566

Jonsen, I. D., Basson, M., Bestley, S., Bravington, M. V., Patterson, T. A., Pedersen, M. W., et al. (2013). State-space models for bio-loggers: a methodological road map. *Deep Sea Res. II* 88–89, 34–46. doi: 10.1016/j.dsr2.2012.07.008

Jonsen, I. D., Flemming, J. M., and Myers, R. A. (2005). Robust state-space modelling of animal movement data. *Ecology* 86, 2874–2880. doi: 10.1890/04-1852

Kaidarova, A., Khan, M. A., Amara, S., Geraldi, N., Shamim, K. A., Wilson, R. P., et al. (2018a). Tunable, Flexible composite magnets for marine monitoring applications. *Adv. Eng. Mater.* 2018:229. doi: 10.1002/adem.201800229

Kaidarova, A., Marengo, M., Marinaro, G., Geraldi, N., Duarte, C. M., and Kosel, J. (2018b). Flexible and biofouling independent salinity sensor. *Adv. Mater. Interfaces* 2018:1801110. doi: 10.1002/admi.201801110

Kays, R., Crofoot, C., Jetz, W., and Wikelski, M. (2015). Terrestrial animal tracking as an eye on life and planet. *Science* 348, 1222–1231. doi: 10.1126/science.aaa2478

Kitade, Y., Shimada, K., Tamura, T., Williams, G. D., Aoki, S., Fukamachi, Y., et al. (2014). Antarctic bottom water production from the Vincennes Bay Polynya, East Antarctica. *Geophys. Res. Lett.*41:2014GL059971 doi: 10.1002/2014GL059971

Krause, J., Krause, S., Arlinghaus, R., Psorakis, I., Roberts, S., and Rutz, C. (2013). Reality mining of animal social systems. *Trends Ecol. Evol.* 28, 541–551. doi: 10.1016/j.tree.2013.06.002

Laidre, K. L., Stirling, I., Lowry, L. F., Wiig, O., Heide-Jørgensen, M. P., and Ferguson, S. H. (2008). Quantifying the sensitivity of Arctic marine mammals to climate-induced habitat change. *Ecol. Appl.* 18:sp2. doi: 10.1890/06-0546.1

Langrock, R., King, R., Matthiopoulos, J., Thomas, L., Fortin, D., and Morales, J. M. (2012). Flexible and practical modeling of animal telemetry data: hidden Markov models and extensions. *Ecology* 93, 2336–2342. doi: 10.1890/11-2241.1

Lawson, G. L., Hückstädt, L. A., Lavery, A. C., Jaffré, F. M., Wiebe, P. H., Fincke, J. R., et al. (2015). Development of an animal-borne "sonar tag" for quantifying prey availability: test deployments on northern elephant seals. *Anim. Biotelemetry* 3:22. doi: 10.1186/s40317-015-0054-7

Lee, K. A., Huveneers, C., Duong, T., and Harcourt, R. G. (2017). The ocean has depth: two-versus three-dimensional space use estimators in a demersal reef fish. *Mar. Ecol. Prog. Ser.* 572, 223–241 doi: 10.3354/meps12097

Lennox, R. J., Aarestrup, K., Cooke, S. J., Cowley, P. D., Deng, Z. D., Fisk, A. T., et al. (2017). Envisioning the future of aquatic animal tracking: technology, science, and application. *Bioscience* 67, 884–896. doi: 10.1093/biosci/bix098

Lennox, R. J., Engler-Palma, C., Kowarski, K., Filous, A., Whitlock, R., Cooke, S. J., et al. (2018). Optimizing marine spatial plans with animal tracking data. *Canad. J. Fish. Aquat. Sci.* 76, 497–509. doi: 10.1139/cjfas-2017-0495

Leos-Barajas, V., Photopoulou, T., Langrock, R., Patterson, T. A., Watanabe, Y. Y., Murgatroyd, M., et al. (2017). Analysis of animal accelerometer data using hidden Markov models. *Methods Ecol. Evol.* 8, 161–173. doi: 10.1111/2041-210X.12657

Lidgard, D. C., Bowen, W. D., Jonsen, I. D., McConnell, B. J., Lovell, P., Webber, D. M., et al. (2014). Transmitting species-interaction data from animal-borne transceivers through Service Argos using Bluetooth communication. *Methods Ecol. Evol.* 5, 864–871. doi: 10.1111/2041-210X.12235

Liew, H. C., Chan, E. H., Papi, F., and Luschi, P. (1995). "Long distance migration of green turtles from Redang Island: the need for regional cooperation in sea turtle conservation," in *Proceedings of the International Congress of Chelonian Conservation. 6-10 July 1995*, ed. B. Devaux, Gonfaron, 73–75.

Lone, K., Merkel, B., Lydersen, C., Kovacs, K. M., and Aars, J. (2018). Sea ice resource selection models for polar bears in the Barents Sea subpopulation. *Ecography* 41, 567–578. doi: 10.1111/ecog.03020

Lydersen, C., Nøst, O. A., Lovell, P., McConnell, B. J., Gammelsrød, T., Hunter, C., et al. (2002). Salinity and temperature structure of a freezing Arctic fjord - monitored by white whales (*Delphinapterus leucas*). *Geophys. Res. Lett.* 29:2119. doi: 10.1029/2002GL015462

Mallett, H. K. W., Boehme, L., Fedak, M. A., Heywood, K. J., Stevens, D. P., and Roquet, F. (2018). Variation in the distribution and properties of Circumpolar Deep Water in the eastern Amundsen Sea, on seasonal timescales, using seal-borne tags. *Geophys. Res. Lett.* 2018:77430. doi: 10.1029/2018GL077430

Manly, B., McDonald, L., Thomas, D., McDonald, T., and Erickson, W. (2002). *Resource Selection by Animals: Statistical Design and Analysis for Field Studies*. Dordrecht: Kluwer.

Mazor, T., Beger, M., McGowan, J., Possingham, H. P. and Kark, S. (2016). The value of migration information for conservation prioritization of sea turtles in the Mediterranean. *Glob Ecol Biogeogr.* 25, 540–552. doi: 10.1111/geb.12434

McCauley, D. J., Pinsky, M. L., Palumbi, S. R., Estes, J. A., Joyce, F. H., and Warner, R. R. (2015). Marine defaunation: animal loss in the global ocean. *Science* 347:1255641. doi: 10.1126/science.1255641

McClintock, B., King, R., Thomas, L., Matthiopoulos, J., McConnell, B., and Morales, J. (2012). A general discrete-time modelling framework for animal movement using multi-scale random walks. *Ecol. Monogr.* 82, 335–349. doi: 10.1890/11-0326.1

McClintock, B. T., Johnson, D. S., Hooten, M. B., Ver Hoef, J. M., and Morales, J. M. (2014). When to be discrete: the importance of time formulation in understanding animal movement. *Mov. Ecol.* 2:21. doi: 10.1186/PREACCEPT-1254967273135270

McConnell, B. J., and Fedak, M. A. (1996). Movements of southern elephant seals. *Canad. J. Zool.* 74, 1485–1496. doi: 10.1139/z96-163

McIntyre, T. (2014). Trends in tagging of marine mammals: a review of marine mammal biologging studies. *Afr. J. Mar. Sci.* 36, 409–422. doi: 10.2989/1814232X.2014.976655

Meekan, M. G., Duarte, C. M., Fernández-Gracia, J., Thums, M., Sequeira, A. M. M., Harcourt, R., et al. (2017). The ecology of human mobility. *Trends Ecol. Evol.* 32, 198–210. doi: 10.1016/j.tree.2016.12.006

Mensah, V., Roquet, F., Siegelman-Charbit, L., Picard, B., Pauthenet, E., and Guinet, C. (2018). A Correction for the thermal mass–induced errors of CTD tags mounted on marine mammals. *J. Atmos. Oceanic Technol.* 35, 1237–1252 doi: 10.1175/JTECH-D-17-0141.1

Meredith, M. P., Nicholls, K. W., Renfrew, I. A., Boehme, L., Biuw, M., and Fedak, M. (2011). Seasonal evolution of the upper-ocean adjacent to the South Orkney Islands, Southern Ocean: Results from a "lazy biological mooring". *Deep Sea Res II* 58, 1569–1579. doi: 10.1016/j.dsr2.2009.07.008

Mernild, S. H., Holland, D. M., Holland, D., Rosing-Asvid, A., Yde, J. C., Liston, G. E., et al. (2015). Freshwater flux and spatiotemporal simulated runoff variability into ilulissat icefjord, west greenland, linked to salinity and temperature observations near tidewater glacier margins obtained using instrumented ringed seals. *J. Phys. Oceanogr.* 45, 1426–1445. doi: 10.1175/JPO-D-14-0217.1

Metcalfe, J. D., Le Quesne, W. J., Cheung, W. W., and Righton, D. A. (2012). Conservation physiology for applied management of marine fish: an overview with perspectives on the role and value of telemetry. *Philos. Trans. R. Soc. Lond. B* 367, 1746–1756. doi: 10.1098/rstb.2012.0017

Michelot, T., Langrock, R., Bestley, S., Jonsen, I. D., Photopoulou, T., and Patterson, T. A. (2017). Estimation and simulation of foraging trips in land-based marine predators. *Ecology* 98, 1932–1944. doi: 10.1002/ecy.1880

Miloslavich, P., Bax, N. J., Simmons, S. E., Klein, E., Appeltans, W., Aburto-Oropeza, O., et al. (2018). Essential ocean variables for global sustained observations of biodiversity and ecosystem changes. *Global Change Biol.* 24, 2416–2433. doi: 10.1111/gcb.14108

Miyazawa, Y., Guo, X., Varlamov, S. M., Miyama, T., Yoda, K., Sato, K., et al. (2015). Assimilation of the seabird and ship drift data in the north-eastern sea of Japan into an operational ocean nowcast/forecast system. *Sci. Rep.* 5:17672. doi: 10.1038/srep17672

Morin, A., Desreumaux, N., Caussin, J. B., and Bartolo, D. (2017). Distortion and destruction of colloidal flocks in disordered environments. *Nat. Phys.* 13, 63–67. doi: 10.1038/nphys3903

Mwaffo, V., Keshavan, J., and Humbert, S. (2018). Detecting intermittent switching leadership in coupled dynamical systems. *Sci. Rep.* 8:10338. doi: 10.1038/s41598-018-28285-1

Nassar, J. M., Khan, S. M., Velling, S. J., Gaxiola, A. D., Shaikh, S. F., Geraldi, N. R., et al. (2018). Compliant lightweight non-invasive standalone "*Marine Skin*" tagging system. *Nat. Flexible Electron.* 2:13. doi: 10.1038/s41528-018-0025-1

Nathan, R., Getz, W. M., Revilla, E., Holyoak, M., Kadmon, R., Saltz, D., et al. (2008). A movement ecology paradigm for unifying organismal movement research. *Proc. Natl. Acad. Sci.* 105, 19052–19059. doi: 10.1073/pnas.0800375105

Newman, P., Dettki, H., and Belbin, L. (2018). What went where when? Representing animal movements as simple darwin core occurrences. *Biodivers. Inform. Sci. Standards* 2:e25664. doi: 10.3897/biss.2.25664

Nguyen, V., Brooks, J. L., Young, L., Lennox, N., Haddaway, R., et al. (2017). To share or not to share in the emerging era of big data: perspectives from fish telemetry researchers on data sharing. *Canad. J. Fish. Aquat. Sci.* 74, 1260–1274. doi: 10.1139/cjfas-2016-0261

Nost, O. A., Biuw, M., Tverberg, V., Lydersen, C., Hattermann, T., Zhou, Q., et al. (2011). Eddy overturning of the Antarctic Slope Front controls glacial melting in the Eastern Weddell Sea. *J. Geophys. Res.* 116:C11. doi: 10.1029/2011JC006965

Ogburn, M. B., Harrison, A.-L., Whoriskey, F., Cooke, S. J., Mills-Flemming, J. E., and Torres, L. G. (2017). Addressing challenges in the application of animal movement ecology to aquatic conservation and management. *Front. Mar. Sci.* 4:70. doi: 10.3389/fmars.2017.00070

Ohshima, K. I., Fukamachi, Y., Williams, G. D., Nihashi, S., Roquet, F., Kitade, Y., et al. (2013). Antarctic Bottom Water production by intense sea-ice formation in the Cape Darnley polynya. *Nat. Geosci.* 6:235. doi: 10.1038/ngeo1738

Padman, L., Costa, D. P., Bolmer, S. T., Goebel, M. E., Huckstadt, L. A., Jenkins, A., et al. (2010). Seals map bathymetry of the Antarctic continental shelf. *Geophys. Res. Lett.* 37:21. doi: 10.1029/2010GL044921

Padman, L., Costa, D. P., Dinniman, M. S., Fricker, H. A., Goebel, M. E., Huckstadt, L. A., et al. (2012). Oceanic controls on the mass balance of Wilkins Ice Shelf, Antarctica. *J. Geophys. Res Oceans* 117:C1. doi: 10.1029/2011JC007301

Park, Y.-H., Roquet, F., Durand, I., and Fuda, J.-L. (2008). Large-scale circulation over and around the Northern Kerguelen Plateau. *Deep Sea Res. II* 55, 566–581. doi: 10.1016/j.dsr2.2007.12.030

Patterson, T. A., Basson, M., Bravington, M. V., and Gunn, J. (2009). Classifying movement behaviour in relation to environmental conditions using hidden Markov models. *J. Anim. Ecol.* 78, 1113–1123. doi: 10.1111/j.1365-2656.2009.01583.x

Patterson, T. A., Thomas, L., Wilcox, C., Ovaskainen, O., and Matthiopoulos, J. (2008). State-space models of individual animal movement. *Trends Ecol. Evol.* 23, 87–94. doi: 10.1016/j.tree.2007.10.009

Pauthenet, E., Roquet, F., Madec, G., Guinet, C., Hindell, M., McMahon, C. R., et al. (2018). Seasonal meandering of the Polar Front upstream of the Kerguelen Plateau. *Geophys. Res. Lett.* 45:614. doi: 10.1029/2018GL 079614

Pellichero, V., Sallée, J.-B., Schmidtko, S., Roquet, F., and Charrassin, J.-B. (2017). The ocean mixed layer under Southern Ocean sea-ice: Seasonal cycle and forcing. *J. Geophys. Res. Oceans* 122, 1608–1633. doi: 10.1002/2016JC 011970

Photopoulou, T., Fedak, M. A., Matthiopoulos, J., McConnell, B., and Lovell, P. (2015). The generalized data management and collection protocol for conductivity-temperature-depth satellite relay data loggers. *Anim. Biotelemetry* 3:21. doi: 10.1186/s40317-015-0053-8

Pickett, M. H., Tang, W., Rosenfeld, L. K., Wash, C. H. (2003). QuikSCAT satellite comparisons with nearshore buoy wind data off the U.S. west coast. *J. Atmos. Ocean Technol.* 20, 1869–1879. doi: 10.1175/1520-0426(2003)020andlt;1869:QSCWNBandgt;2.0.CO;2

Pirotta, V., Grech, A., Jonsen, I. D., Laurance, W. F., and Harcourt, R. G. (2019). Consequences of global shipping traffic for marine giants. *Front. Ecol. Environ.* 17, 39–47. doi: 10.1002/fee.1987

Queiroz, N., Humphries, N. E., Mucientes, G., Hammerschlag, N., Lima, F. P., Scales, K. L., et al. (2016). Ocean-wide tracking of pelagic sharks reveals extent of overlap with longline fishing hotspots. *Proc. Natl. Acad. Sci. U.S.A.* 113, 1582–1587. doi: 10.1073/pnas.1510090113

Raymond, B., Lea, M. A., Patterson, T., Andrews-Goff, V., Sharples, R., Charrassin, J. B., et al. (2015). Important marine habitat off east Antarctica revealed by two decades of multi-species predator tracking. *Ecography* 38, 121–129. doi: 10.1111/ecog.01021

Riser, S. C., Freeland, H. J., Roemmich, D., Wijffels, S., Troisi, A., Belbéoch, M., et al. (2016). Fifteen years of ocean observations with the global Argo array. *Nat. Climate Change* 6:145. doi: 10.1038/nclimate2872

Rodríguez, J. P., Fernández-Gracia, J., Thums, M., Hindell, M. A., Sequeira, A. M., Meekan, M. G., et al. (2017). Big data analyses reveal patterns and drivers of the movements of southern elephant seals. *Sci. Rep.* 7:112. doi: 10.1038/s41598-017-00165-0

Roemmich, D., Johnson, G. C., Riser, S., Davis, R., Gilson, J., Owens, W. B., et al. (2009). The Argo Program: Observing the global ocean with profiling floats. *Oceanography* 22, 34–43. doi: 10.5670/oceanog.2009.36

Roquet, F., Boehme, L., Block, B., Charrassin, J. B., Costa, D., Guinet, C., et al. (2017). Ocean observations using tagged animals. *Oceanography* 30:139. doi: 10.5670/oceanog.2017.235

Roquet, F., Charrassin, J. B., Marchand, S., Boehme, L., Fedak, M., Reverdin, G., et al. (2011). Delayed-mode calibration of hydrographic data obtained from animal-borne satellite relay data loggers. *J. Atmos. Ocean Technol.* 28, 787–801. doi: 10.1175/2010JTECHO801.1

Roquet, F., Park, Y.-H., Guinet, C., Bailleul, F., and Charrassin, J.-B. (2009). Observations of the Fawn Trough Current over the Kerguelen Plateau from instrumented elephant seals. *J. Mar. Syst.* 78, 377–393. doi: 10.1016/j.jmarsys.2008.11.017

Roquet, F., Williams, G. D., Hindell, M., Harcourt, R., McMahon, C., Guinet, C., et al. (2014). A Southern Indian Ocean database of hydrographic profiles obtained with instrumented elephant seals. *Nat. Sci. Data* 1:140028. doi: 10.1038/sdata.2014.28

Roquet, F., Wunsch, C., Forget, G., Heimbach, P., Guinet, C., Reverdin, G., et al. (2013). Estimates of the Southern Ocean general circulation improved by animal-borne instruments. *Geophys. Res. Lett.* 40, 6176–6180. doi: 10.1002/2013GL058304

Sallée, J.-B. (2018). Southern ocean warming. *Oceanography* 31, 52–62. doi: 10.5670/oceanog.2018.215

Sánchez-Román, A., Gómez-Navarro, L., Fablet, R., Oro, D., Mason, E., Arcos, J. M., et al. (2019). Rafting behaviour of seabirds as a proxy to describe surface ocean currents in the Balearic Sea. *Sci. Rep.* 9:17775. doi: 10.1038/s41598-018-36819-w

Sasaki, T., and Biro, D. (2017). Cumulative culture can emerge from collective intelligence in animal groups. *Nat. Commun.* 8:15049. doi: 10.1038/ncomms15049

Schick, R. S., Loarie, S. R., Colchero, F., Best, B. D., Boustany, A., Conde, D. A., et al. (2008). Understanding movement data and movement processes: current and emerging directions. *Ecol. Lett.* 11, 1338–1350. doi: 10.1111/j.1461-0248.2008.01249.x

Seminoff, J. A. (2004). *Chelonia mydas*. The IUCN Red List of Threatened Species 2004:e.T4615A11037468.

Sequeira, A. M. M., Rodríguez, J. P., Eguíluz, V. M., Harcourt, R., Hindell, M., Sims, D. W., et al. (2018). Convergence of marine megafauna movement patterns in coastal and open oceans. *Proc. Natl. Acad. Sci.* 115, 3072–3077. doi: 10.1073/pnas.1716137115

Shaffer, S. A., Tremblay, Y., Weimerskirch, H.,Scott, D., Thompson, D. R., Sagar, P. M., et al. (2006). Migratory shearwaters integrate oceanic resources across the Pacific Ocean in an endless summer. *Proc. Natl. Acad. Sci.* 103, 12799–12802. doi: 10.1073/pnas.0603715103

Silvano, A., Rintoul, S. R., Peña-Molino, B., Hobbs, W. R., van Wijk, E., Aoki, S., et al. (2018). Freshening by glacial meltwater enhances melting of ice shelves and reduces formation of Antarctic Bottom Water. *Sci. Adv*. 4:eaap9467. doi: 10.1126/sciadv.aap9467

Simpfendorfer, C. A., Olsen, E. M., Heupel, M. R., and Moland, E. (2012). Three-dimensional kernel utilization distributions improve estimates of space use in aquatic animals. *Canad. J. Fish. Aquat. Sci.* 69, 565–572. doi: 10.1139/f 2011-179

Sims, D. W., Southall, E. J., Humphries, N. E., Hays, G. C., Bradshaw, C. J., Pitchford, J. W., et al. (2008). Scaling laws of marine predator search behaviour. *Nature* 451, 1098–1103. doi: 10.1038/nature06518

Sims, D. W., Witt, M. J., Richardson, A. J., Southall, E. J., and Metcalfe, J. D. (2006). Encounter success of free-ranging marine predator movements across a dynamic prey landscape. *Proc. R. Soc. B Biol. Sci.* 273, 1195–1201. doi: 10.1098/rspb.2005.3444

Sousa, L., Queiroz, N., Mucientes, G., Humphries, N., and Sims, D. (2016). Environmental influence on the seasonal movements of satellite-tracked ocean sunfish *Mola mola* in the north-east Atlantic. *Anim. Biotelemetry* 4:2. doi: 10.1186/s40317-016-0099-2

Straneo, F., Hamilton, G. S., Sutherland, D. A., Stearns, L. A., Davidson, F., Hammill, M. O., et al (2010). Rapid circulation of warm subtropical waters in a major glacial fjord in East Greenland. *Nat. Geosci.* 3, 182–186. doi: 10.1038/ngeo764

Strøm, J. F., Thorstad, E. B., Hedger, R. D., and Rikardsen, A. H. (2018). Revealing the full ocean migration of individual Atlantic salmon. *Anim. Biotelemetry* 6:2. doi: 10.1186/s40317-018-0148-0

Sutherland, D. A., Straneo, F., Stenson, G. B., Davidson, F. J. M., Hammill, M. O., and Rosing-Asvid, A. (2013). Atlantic water variability on the SE Greenland continental shelf and its relationship to SST and bathymetry. *J. Geophys. Res. Oceans* 118, 847–855. doi: 10.1029/2012JC0 08354

Teo, S. L., Boustany, A., Blackwell, S., Walli, A., Weng, K. C., and Block, B. A. (2004). Validation of geolocation estimates based on light level and sea surface temperature from electronic tags. *Mar. Ecol. Prog. Ser.* 283, 81–98. doi: 10.3354/meps283081

Thums, M., Fernández-Gracia, J., Sequeira, A. M. M., Eguíluz, V. M., Duarte, C. M., and Meekan, M. G. (2018). How big data fast tracked human mobility research and the lessons for animal movement ecology. *Front. Mar. Sci.* 2018:21. doi: 10.3389/fmars.2018. 00021

Treasure, A. M., Roquet, F., Ansorge, I. J., Bester, M. N., Boehme, L., Bornemann, H., et al. (2017). Marine mammals exploring the oceans pole to pole a review of the MEOP consortium. *Oceanography* 30, 132–138. doi: 10.5670/oceanog.2017.234

Turchin, P. (1998). *Quantitative Analysis of Movement*. Sunderland, MA: Sinauer Associates.

Tverberg, V., Nøst, O. A., Lydersen, C., and Kovacs, K. M. (2014). Winter sea ice melting in the Atlantic Water subduction area, Svalbard Norway. *J. Geophys. Res. Oceans* 119, 5945–5967. doi: 10.1002/2014JC0 10013

Udyawer, V., Dwyer, R., Hoenner, X., Babcock, R., Brodie, S., Campbell, H., et al. (2018). Movement ecology in an era of big data: a framework for standardising analysis of animal telemetry data. *Anim. Biotelemetry*. 6:17. doi: 10.1186/s40317-018-0162-2

Udyawer, V., Simpfendorfer, C., and Heupel, M. (2015). Diel patterns in the three-dimensional use of space by sea snakes. *Anim. Biotelemetry* 3:6. doi: 10.1186/s40317-015-0063-6

Van de Merwe, J., Ibrahim, K., Lee, S. Y., and Whittier, J. M. (2009). Habitat use by green turtles (*Chelonia mydas*) nesting in Peninsular Malaysia: local and regional conservation implications. *Wildlife Res*. 36, 637–645. doi: 10.1071/WR09099

Vandenabeele, S. P., Shepard, E. L., Grogan, A., and Wilson, R. P. (2012). When three per cent may not be three per cent; device-equipped seabirds experience variable flight constraints. *Mar. Biol.* 159, 1–14. doi: 10.1007/s00227-011-1784-6

Vicsek, T., and Zafeiris, A. (2012). Collective motion. *Phys. Rep. Rev. Sec. Phys. Lett.* 517, 71–140. doi: 10.1016/j.physrep.2012.03.004

Whitlock, R. E., Hazen, E. L., Walli, A., Farwell, C., Bograd, S. J., Foley, D. G., et al. (2015). Direct quantification of energy intake in an apex marine predator suggests physiology is a key driver of migrations. *Sci. Adv.* 1:e1400270. doi: 10.1126/sciadv. 1400270

Whoriskey, K., Auger-Methé, M., Albertsen, C. M., Whoriskey, F. G., Binder, T. R., Krueger, C. C., et al. (2017). A hidden Markov movement model for rapidly identifying behavioral states from animal tracks. *Ecol. Evol.* 7, 2112–2121. doi: 10.1002/ece3.2795

Wikelski, M., and Kays, R. (2010). *Movebank: Archive, Analysis and Sharing of Animal Movement Data*. Available online at: https://www.movebank.org/

Williams, G. D., Herraiz-Borreguero, L., Roquet, F., Tamura, T., Ohshima, K. I., Fukamachi, Y., et al. (2016). The suppression of Antarctic bottom water formation by melting ice shelves in Prydz Bay. *Nat. Commun.* 7:12577doi: 10.1038/ncomms12577

Williams, G. D., Hindell, M., Houssais, M.-N., Tamura, T., and Field, I. C. (2011). Upper ocean stratification and sea ice growth rates during the summer-fall transition, as revealed by Elephant seal foraging in the Adelie Depression, East Antarctica. *Ocean Sci.* 7, 185–202. doi: 10.5194/os-7-185 -2011

World Economic Forum (2017). *Harnessing the Fourth Industrial Revolution for Oceans*. 25. Available online at: http://www3.weforum.org/docs/WEF_Harnessing_4IR_Oceans.pdf

Xavier, J. C., Cherel, Y., Ceia, F. R., Queirós, J. P., Guimarães, B., Rosa, R., et al. (2018). Eastern rockhopper penguins *Eudyptes filholi* as biological samplers of juvenile and sub-adult cephalopods around Campbell Island, New Zealand. *Polar Biol.* 41, 1937–1949. doi: 10.1007/s00300-018-2333-2

Xu, Z., Gao, G., Xu, J., and Shi, M. (2017). The evolution of water property in the Mackenzie Bay polynya during Antarctic winter. *J. Ocean Univ. China* 16, 766–774. doi: 10.1007/s11802-017-3286-8

Yoda, K., Shiomi, K., and Sato, K. (2014). Foraging spots of streaked shearwaters in relation to ocean surface currents as identified using their drift movements. *Prog. Oceanogr.* 122, 54–64. doi: 10.1016/j.pocean.2013.12.002

Yonehara, Y., Goto, Y., Yoda, K., Watanuki, Y., Young, L. C., Weimerskirch, H., et al. (2016). Flight paths of seabirds soaring over the ocean surface enable measurement of fine-scale wind speed and direction. *Proc. Natl. Acad. Sci.* 113, 9039–9044. doi: 10.1073/pnas.1523853113

Zhang, X., Thompson, A. F., Flexas, M. M., Roquet, F., and Bornemann, H. (2016). Circulation and meltwater distribution in the Bellingshausen Sea: from shelf break to coast. *Geophys. Res. Lett.* 43, 6402–6409. doi: 10.1002/2016GL068998

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WebCAT: Piloting the Development of a Web Camera Coastal Observing Network for Diverse Applications

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Web cameras are transforming coastal environmental monitoring. Improvements in camera technology and image processing capabilities, paired with decreases in cost, enable widespread use of camera systems by researchers, managers and first responders for a growing range of environmental monitoring applications. Applications are related to transportation and commerce, preparedness, risk reduction and response, and stewardship of coastal resources. While web cameras are seemingly ubiquitous, operators often follow unique installation procedures and collect, store, and process imagery data in various ways. These inconsistencies significantly limit the ability for imagery data to be shared and utilized across research and operational disciplines. Similar to the early days of other remote sensing networks like High Frequency Radar, the benefits and downstream application of coastal imagery data can be greatly enhanced through centralized data access and standardization of data collection, analysis and dissemination. The NOAA National Ocean Service Web Camera Applications Testbed (WebCAT) was launched in 2017 in partnership with SECOORA, as a public-private partnership to address this coastal ocean observing standardization need. WebCAT is a pilot project relying on the private sector expertise of Surfline, Inc., to install and operate several web cameras capable of meeting the short-term needs of diverse users including NOAA, USGS, state health agencies, academia and others. The project aims to determine operational imagery collection, storage, processing, access, and archival requirements that will foster collaboration across research and operational user communities. Seven web cameras have been installed at six locations along the southeast United States coast (from Florida to North Carolina) for purposes including: counting animals on the beach and migrating right whales, identifying rip currents, validating wave runup models, and understanding human use of natural resources. Here we present a review of the state of coastal imagery data and an overview of the WebCAT project. Goals of an upcoming community workshop will also be presented along with our vision for how WebCAT can motivate a future sustained operational web camera network.

Keywords: webcam, coastal observations, observing network, environmental monitoring, video imagery

INTRODUCTION

Over the past several decades coastal imagery has become a proven and invaluable tool for remote sensing of the coastal environment. Uses for imagery data range from coastal morphological change, to surf zone hydrodynamics, to beach attendance and safety, and even to detecting marine debris. Fixed position cameras for scientific coastal monitoring have been in use since the 1980s with the Argus systems the most well-known and utilized (Holman and Stanley, 2007), along with several other systems and approaches (Pearre and Puleo, 2009; Nieto et al., 2010; Brignone et al., 2012; Taborda and Silva, 2012). These systems typically consist of one or more stationary cameras at well elevated positions with a wide field-of-view, onsite computer for image processing and file transfer, and a set of algorithms that use individual pixels or groups of pixels for monitoring coastal features and processes. Although use of these types of systems have expanded as cameras have become smaller and more cost effective, there are challenges preventing widespread installation. These challenges include difficulties in finding suitable site infrastructure or an appropriate host; expertise needed for system installation and data processing; and costs associated with system installation, operation and maintenance.

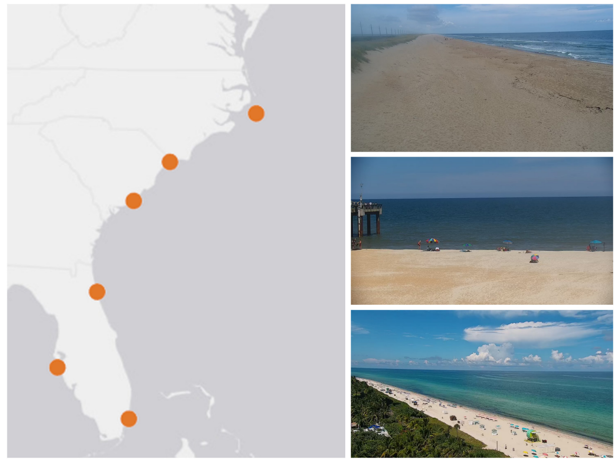

FIGURE 1 | The six pilot WebCAT webcam locations (left) and example snapshots from the webcams in Buxton, NC (top right), St. Augustine Pier, FL (middle right) and Miami, FL (bottom right). The other webcam locations (not shown) include North Myrtle Beach, SC, Folly Beach, SC, and Bradenton, FL.

Web cameras (sometimes called surfcams or webcams) have emerged as a potential alternative or complement to coastal imagery systems established for scientific use. Webcams are small, stand-alone and relatively inexpensive camera systems, which may have either remote or onsite data acquisition, processing, and analysis. A typical webcam installation consists of a single robotic pan-tilt-zoom camera, which can rotate to provide the field-of-view range of a multi-camera system. Webcams are already widely used for a range of activities including observing surf conditions, news and weather reporting, beach safety, and monitoring recreational beach use. Due to these use cases, an extensive network of coastal webcams already exists. For instance, there are over 500 cams on the Surfline network alone[1]. Researchers relied on a similarly extensive network in Australia to investigate webcam use for wave observations and shoreline monitoring (Splinter et al., 2011; Mole et al., 2013; Bracs et al., 2016), and were able to demonstrate acceptable shoreline monitoring performance. Though researchers in the United States have begun to install and utilize webcams for similar research objectives, more standardized use of webcam infrastructure and resulting downstream imagery products has yet to be realized.

Here we present the Web Camera Application Testbed (WebCAT), a public-private partnership to develop a sustained operational webcam network with standardized imagery data acquisition and processing for a range of downstream applications. The testbed relies on the private sector expertise of Surfline, Inc., to install and operate seven webcams at six locations along the United States southeast Atlantic and Gulf coasts (**Figure 1**), and partners with the National Oceanic and Atmospheric Administration (NOAA) National Ocean Service (NOS) and National Weather Service (NWS), the Southeast Coastal Ocean Observing Regional Association (SECOORA), the United States Geological Survey (USGS), and academic and state partners to store, process, and analyze the imagery data. The installation locations for the testbed were selected based on the availability of suitable installation infrastructure and initial research use cases. The initial use cases identified include: observations of coastal hazards (e.g., rip currents and wave runup), identification of both beach and marine fauna (e.g., right whales), and assessing human use of natural resources, though potential uses are likely much broader.

This initial pilot project is a proof-of-concept for both the public-private partnership model and for the standardization of webcam imagery data acquisition, processing, storage and delivery. As a model for success, one needs to look no further than High Frequency (HF) Radar. The HF Radar national network is a coastal ocean current remote sensing network which initially started as an academic research endeavor in the 1990s and now consists of a nationwide operational network of more than 100 radars (Harlan et al., 2010). Users can access near real-time ocean surface current data via the network in a standard format for any location across the United States, thus enabling widespread downstream use of HF Radar data. A similar potential exists for coastal webcam imagery data; webcams operated by private industry, academic, federal, regional or local partners share standardized imagery data with a regional (e.g., SECOORA, other IOOS regional associations) or federal (NOAA and USGS) centralized repository. Single site access to standardized coastal imagery data has the potential to spark innovation beyond traditional research applications to the realm of widespread operational use.

This paper will first describe the broad range of applications that have utilized coastal imagery data. The WebCAT network and methodology will then be described along with descriptions of initial applications. Lastly, both near-term (months to

[1]www.surfline.com

years) and long-term (years to decades) goals for WebCAT will be presented.

IMAGERY TO MONITOR THE COASTAL ENVIRONMENT

Over the past several decades coastal imagery data has been used for a wide range of research applications. Imagery data related to hydrodynamics and morphodynamics has been predominantly acquired and processed via the well-established Argus camera systems (Holman and Stanley, 2007; Holman and Haller, 2013), though more recently other camera or webcam systems have been utilized for coastal monitoring. The uses for coastal imagery can be broken into categories of coastal morphological change, hydrodynamics, human impact on coastal resources, and ecological, environmental and water quality observations.

Coastal Morphological Change

Perhaps the most widespread and studied use of coastal imagery data is to observe and measure coastal morphological change. Some initial uses of Argus imagery quantified sandbar morphology using time-averaged (i.e., time-exposure) imagery (Lippmann and Holman, 1989; van Enckevort and Ruessink, 2003). As described in Holman and Stanley (2007), averaging 10 min of individual surf zone images captured every 2 Hz produces an image where bright intensity pixels indicate waves consistently breaking and denote shallow water, and dark intensity pixels indicate the absence of breaking waves and relatively deeper water (**Figure 2**). Non-moving features appear as they do in a snapshot. A time series of these time-exposure images over days to years demonstrates changing surf zone morphology including the presence of sand bars and rip current channels.

Imagery data has also been frequently used for the identification and quantification of shoreline change (Aarninkhof et al., 2003; Plant et al., 2007; Pearre and Puleo, 2009; Harley et al., 2014; Pianca et al., 2015; Didier et al., 2017). Typically this involves utilizing the time-exposure imagery and relying on image characteristics such as pixel brightness and pixel color to identify the shoreline position, which can then be tracked over time.

Measuring surf zone bathymetry is another application of coastal imagery data that has seen recent advancements. Beyond the more qualitative assessments enabled by time-exposure imagery, assimilation of imagery into a numerical model has produced reasonably accurate estimates of the surf zone bathymetry (van Dongeren et al., 2008). The algorithm cBathy (Holman et al., 2013), tracks wave crests in imagery over time to inversely determine depth from the dispersion relation of waves in intermediate or shallow water. The approach is accurate and robust compared to vessel-based surveys during relatively low wave height conditions (Brodie et al., 2018). Imagery derived bathymetry has also been assimilated into hydrodynamic models to predict nearshore circulation and flow features like rip currents (Wilson et al., 2014).

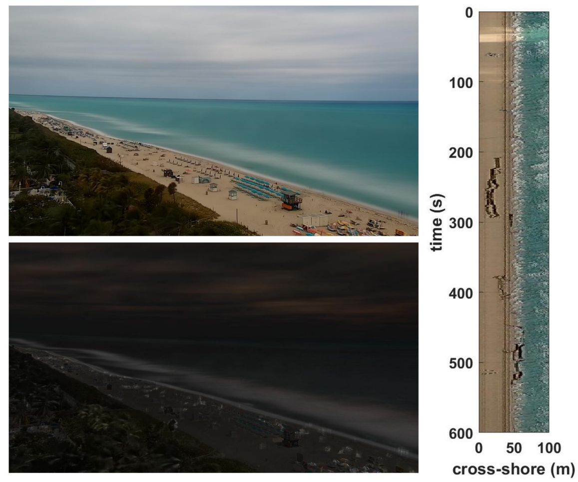

FIGURE 2 | An example time-exposure (top), time-variance (bottom) and time-stack (right) imagery from the Miami, FL webcam at 1200 UTC on March 10, 2018. Note the white pixels varying along the beach that indicate where waves are breaking in the time-exposure image.

Hydrodynamics

Rip currents are a fundamental surf zone circulation feature that are important to observe due to the hazard posed to swimmers. Rip currents (or more precisely rip current channels) can be observed in time-exposure imagery as darker pixels extending through the region of brighter pixels denoting waves breaking over a sandbar (Lippmann and Holman, 1989). Rip current occurrence has been quantified over space and time for different coastal locations using this approach (Holman et al., 2006; Turner et al., 2007). Non-stationary or transient rips (i.e., not forced by the surf zone bathymetry) have been similarly observed by relying on alongshore variations in the time-variance imagery (Long and Ozkan-Haller, 2016). Attempts have also been made to automate the identification of rip currents in time-exposure imagery (Pitman et al., 2016).

Additional information about surf zone circulation and flow can be observed by tracking foam on the surface of the water using imagery time series. For instance, the flow speed of longshore currents can be measured by tracking the temporal and alongshore position of foam (Chickadel et al., 2003; Almar et al., 2016). Though computationally intensive, some progress has been made on utilizing the two dimensional motion of foam and other particles through particle image velocimetry (PIV). This approach has observed both swash (Holland et al., 2001) and surf zone current velocity fields (Puleo et al., 2003). More recently a similar approach known as optical flow estimation has observed flow fields in the surf zone with some skill compared to *in situ* observations (Derian and Almar, 2017).

In addition to currents, coastal imagery has been used to observe wave characteristics. Wave runup, or the time-varying, shoreward extent of breaking waves at the shoreline, is typically observed using time-stacks of imagery data (**Figure 2**; Holman and Guza, 1984; Holland et al., 1995; Stockdon et al., 2006). This approach tracks the maximum landward extent of wave runup at one alongshore location over time, and can help explain storm-induced morphological change including beach and dune erosion and overwash. Progress has also been made in measuring wave characteristics from surf zone imagery. Wave period and peak wave direction can be estimated (Herbers and Guza, 1990; Stockdon and Holman, 2000), but the ability to measure wave height has been limited, and typically requires multiple-cameras for stereo imaging (Bechle and Wu, 2011; de Vries et al., 2011; Shand et al., 2012). Lastly, other hydrodynamic topics explored via imagery data include observing internal waves (Suanda et al., 2014) and tracking movement of coastal sea ice (Druckenmiller et al., 2009).

Human Impact on Coastal Resources

Coastal imagery has also been widely used outside of the realm of physical processes. Perhaps most common is the use of imagery to identify and quantify beach users for the purposes of coastal zone management. This typically involves the development of an automated person counting method, which is then applied to a coastal region to analyze beach use over time (Green et al., 2005; Guillen et al., 2008; Balouin et al., 2014). Preferred locations of beach users can also be assessed to determine association with potential hazards (Silva-Cavalcanti et al., 2018) and to support beach management by relating use to beach carrying capacity (Jimenez et al., 2007; Cisneros et al., 2016). Marine debris or beach litter can also be identified and spatially and temporally tracked using imagery (Kako et al., 2010; Kataoka et al., 2012). Debris on the beach were identified based on pixel color and the relative differences from the surrounding beach or coastal background. Physical mechanisms leading to debris occurrence and position on the beach has been established (Kako et al., 2018).

Ecological, Environmental and Water Quality Observations

Though coastal applications are thus far limited, recent efforts have demonstrated the ecological and environmental monitoring capabilities of webcam or other stationary imagery (Bradley and Clarke, 2011). These include quantifying the increases in forested extent for an alpine treeline ecotone (Roush et al., 2007), monitoring deciduous autumnal color change (Astola et al., 2008), calculating normalized snow indices from ground-based cameras (Hinkler et al., 2002), comparing the "green-up" signal to canopy photosynthesis data (Richardson et al., 2007, 2009), and tracking the development of invasive Pepperweed (Sonnentag et al., 2011). Though not relying on a webcam, a smartphone camera app has been developed and tested to perform above water observations of water quality including suspended sediment, chlorophyll and dissolved organic matter (Leeuw and Boss, 2018). Presumably webcams could be used for similar types of observations.

THE WEB CAMERA APPLICATION TESTBED

The WebCAT was initiated to meet short-term coastal observation needs and to pilot a proposed model for a public-private partnership to develop a web camera observation network. As described above, coastal imagery data is widely used for a range of applications in the research community. However, data acquisition, delivery and processing varies depending on the camera type, operator and end use. WebCAT seeks to standardize these aspects of the collection of coastal webcam imagery to maximize data access and the benefit for a range of end use applications. The observation needs initially identified include observing and quantifying wave runup, rip current occurrence, beach use and counting fauna on land and in the ocean. These use cases, coupled with existing infrastructure and host availability largely dictated the locations for camera installation (**Figure 1** and **Table 1**). The camera installation and data acquisition was handled by Surfline, Inc., and their expertise and pre-existing infrastructure minimized cost and made the process much more efficient than it would have been otherwise. SECOORA and Axiom utilized their existing web services to host the near real-time and archived imagery data and developed a site to deliver the data to end users[2]. The data page includes denoting camera downtime, which can occur for a variety of reasons including camera malfunction (there were several lightning strikes at the Miami camera), as well as modifications or errors in the data transmission system. Data users such as NOAA, USGS and academic partners are applying downstream processing methods for specific end use applications.

Surfline installed seven webcams for the WebCAT project. After an initial prioritization process with the stakeholders, Surfline spent several months searching for suitable hosts. Site reviews were conducted at each location to ensure suitability for the project. Host agreements were made with property owners of each location, which outline privacy, liability, right to terminate and other considerations. High Definition PTZ IP

[2] secoora.org/webcat

TABLE 1 | WebCAT camera specific information and metadata.

Camera location	Stationary (S) or panning (P)	Surveyed (y/n)	Elevation above ground (m)	Primary purpose
Buxton, NC	S	Y	10	Runup
North Myrtle Beach, SC	S	N	15	Beach use and water quality; rip currents
Folly Beach, SC (north and south)	S (north) P (south)	N	15 15	General monitoring
St. Augustine, FL	P	N	10	Whale monitoring
Miami, FL	S	Y	40	Rip currents; runup
Bradenton, FL	S	N	5	Rip currents

cameras were installed at each site with a minimum imagery resolution of 1280×720, a sampling rate of 30 Hz (or frames per second) and a bitrate of 1500 kbps. Imagery data was made operational via existing Surfline processes and technologies. For example, Surfline already stores camera streams on Amazon Web Services (AWS) to allow their users access to the data in ten minute increments. This process was replicated for these installations, and data access was provided to Axiom who in turn made archived imagery data available to project stakeholders. In addition, Surfline had existing processes to share live streams of their cams with partners, which allowed seamless syndication of the cams on the SECOORA WebCAT website. In addition, site surveys and additional calibrations were performed at two locations (Buxton, NC and Miami, FL) to aid in converting image coordinates to real world coordinates. Standard practice for converting to real world coordinates includes intrinsic calibrations, which account for lens distortion, and extrinsic calibrations, which account for camera position and look angles, and applying standard photogrammetric relationships (Holland et al., 1997).

Several cameras (initially Miami, FL and Bradenton, FL) will be used to aid in rip current identification and were selected in part because a NOAA rip current forecast model is being validated at those locations (Dusek and Seim, 2013). Initially the time-exposure imagery will be utilized to manually identify rip currents during select time periods, however, approaches to identify rip currents in an automated or machine learning approach are also being explored. Images from select cameras with sufficiently high viewpoints and camera calibration measurements (Miami, FL and Buxton, NC) are being used to create wave runup time-stacks for extracting water levels at the shoreline and validating total water level models[3]. Imagery is also being used as a means to count and inventory items and activities along swimming beaches and the nearshore. Explorations include automated identification and counting of pets and birds, which may be correlated to bacterial loading and corresponding swimming beach water quality forecasts. Similarly, identification and monitoring of St. Augustine-based migrating right whales will enable the correlation of imagery-based and in-person sightings.

There were some challenges in developing the pilot WebCAT network. Finding a suitable host for new camera installations was particularly difficult. This is a common issue with camera installation, as private businesses and residences are often hesitant to participate. In some cases, this challenge resulted in camera locations, and particularly camera elevations, being less than ideal for some applications. Another challenge was installing the camera to meet the broadest range of needs for each installation. For applications where camera stability isn't as important (e.g., counting people or animals), a panning camera is preferred to maximize field-of-view. However, for applications where stability is essential (e.g., wave runup calculations) a panning camera potentially introduces more error than is desirable (Bracs et al., 2016).

[3]coastal.er.usgs.gov/hurricanes/research/twlviewer/

A FUTURE OPERATIONAL WEB CAMERA OBSERVING SYSTEM

The WebCAT project will focus on continuing to enhance standardized data delivery over the near-term. For instance, investigating how best to include the downstream processing common in other scientific monitoring stations including time-exposure images, variance images and time-stacks as part of standard imagery products accessible to end users. One potential approach is to process imagery in near real-time, as each 10-min video segment is available for download. Users could then download only the processed images, potentially including rectified imagery where possible, instead of having to download the full video and perform this processing locally. An important consideration when standardizing and optimizing how to deliver webcam coastal imagery data is coordinating the needs of both the established coastal imagery research community and operational end users (e.g., NOAA, USGS, etc.). A recent coastal webcam workshop brought these user groups together to identify and document universal requirements and best practices for webcam installation, imagery acquisition, delivery, and processing. Further, it is envisioned that an ongoing community of practice will be initiated to ensure the processes, successes and lessons learned are carried forward beyond the initial WebCAT pilot.

In the long-term the WebCAT project lays the groundwork for a potential future nationwide webcam coastal ocean observing network. Similar to the HF Radar network and other national coastal observing networks, it is envisioned that common data collection and QA/QC procedures (IOOS, 2016) and data and metadata formats will be followed by all systems existing within the network. This standardization will enable the imagery data to be provided through regional hubs or websites of individual institutions or providers while also being available through a national centralized repository. This standardization will also ensure that a data user can easily access high quality imagery data for their specific application from potentially hundreds of different coastal locations throughout the United States regardless of the webcam operator. However, unlike other coastal observing networks the relatively low costs associated with webcam installation, operation and maintenance will equate to a wide range of data providers including federal, private (e.g., Surfline), academic, regional (SECOORA) and local partners. If this vision is achieved, webcam coastal imagery will transform environmental monitoring along our coastlines.

AUTHOR CONTRIBUTIONS

GD was the primary author. DH was the project lead and contributed to the text. MW was the webcam lead and contributed to the text. JB created **Figure 2** and contributed to the text. JL and DP provided the references and contributed to the text. TV contributed to the text and reviewed.

REFERENCES

Aarninkhof, S. G. J., Turner, I. L., Dronkers, T. D. T., Caljouw, M., and Nipius, L. (2003). A video-based technique for mapping intertidal beach bathymetry. *Coast. Eng.* 49, 275–289. doi: 10.1016/S0378-3839(03)00064-64

Almar, R., Larnier, S., Castelle, B., Scott, T., and Floc'h, F. (2016). On the use of the Radon transform to estimate longshore currents from video imagery. *Coast. Eng.* 114, 301–308. doi: 10.1016/j.coastaleng.2016.04.016

Astola, H., Molinier, M., Mikkola, T., and Kubin, E. (2008). "Web cameras in automatic autumn colour monitoring," in *Proceedings of the IEEE International Geoscience and Remote Sensing Symposium*, (Boston, MA: IEEE), 824–827.

Balouin, Y., Rey-Valette, H., and Picand, P. A. (2014). Automatic assessment and analysis of beach attendance using video images at the Lido of Sete beach, France. *Ocean Coast. Manag.* 102, 114–122. doi: 10.1016/j.ocecoaman.2014.09.006

Bechle, A. J., and Wu, C. H. (2011). Virtual wave gauges based upon stereo imaging for measuring surface wave characteristics. *Coast. Eng.* 58, 305–316. doi: 10.1016/j.coastaleng.2010.11.003

Bracs, M. A., Turner, I. L., Splinter, K. D., Short, A. D., Lane, C., Davidson, M. A., et al. (2016). Evaluation of opportunistic shoreline monitoring capability utilizing existing "Surfcam" infrastructure. *J. Coast. Res.* 32, 542–554. doi: 10.2112/Jcoastres-D-14-00090.1

Bradley, E. S., and Clarke, K. C. (2011). Outdoor webcams as geospatial sensor networks: challenges, issues and opportunities. *Cartogr. Geogr. Inf. Sci.* 38, 3–19. doi: 10.1559/152304063813

Brignone, M., Schiaffino, C. F., Isla, F. I., and Ferrari, M. (2012). A system for beach video-monitoring: beachkeeper plus. *Comput. Geosci.* 49, 53–61. doi: 10.1016/j.cageo.2012.06.008

Brodie, K. L., Palmsten, M. L., Hesser, T. J., Dickhudt, P. J., Raubenheimer, B., Ladner, H., et al. (2018). Evaluation of video-based linear depth inversion performance and applications using altimeters and hydrographic surveys in a wide range of environmental conditions. *Coast. Eng.* 136, 147–160. doi: 10.1016/j.coastaleng.2018.01.003

Chickadel, C. C., Holman, R. A., and Freilich, M. H. (2003). An optical technique for the measurement of longshore currents. *J. Geophys. Res. Ocean* 108:3364. doi: 10.1029/2003jc001774

Cisneros, M. A. H., Sarmiento, N. V. R., Delrieux, C. A., Piccolo, M. C., and Perillo, G. M. E. (2016). Beach carrying capacity assessment through image processing tools for coastal management. *Ocean Coast. Manag.* 130, 138–147. doi: 10.1016/j.ocecoaman.2016.06.010

de Vries, S., Hill, D. F., de Schipper, M. A., and Stive, M. J. F. (2011). Remote sensing of surf zone waves using stereo imaging. *Coast. Eng.* 58, 239–250. doi: 10.1016/j.coastaleng.2010.10.004

Derian, P., and Almar, R. (2017). Wavelet-based optical flow estimation of instant surface currents from shore-based and UAV videos. *IEEE Trans. Geosci. Remote Sens.* 55, 5790–5797. doi: 10.1109/Tgrs.2017.2714202

Didier, D., Bernatchez, P., Augereau, E., Caulet, C., Dumont, D., Bismuth, E., et al. (2017). LiDAR validation of a video-derived beachface topography on a tidal flat. *Remote Sens.* 9:826. doi: 10.3390/rs9080826

Druckenmiller, M. L., Eicken, H., Johnson, M. A., Pringle, D. J., and Williams, C. C. (2009). Toward an integrated coastal sea-ice observatory: system components and a case study at Barrow, Alaska. *Cold Reg. Sci. Technol.* 56, 61–72. doi: 10.1016/j.coldregions.2008.12.003

Dusek, G., and Seim, H. (2013). A probabilistic rip current forecast model. *Journal of Coastal Research* 29, 909–925. doi: 10.2112/Jcoastres-D-12-00118.1

Green, S., Blumenstein, M., Browne, M., and Tomlinson, R. (2005). "The detection and quantification of persons in cluttered beach scenes using neural network-based classification," in *Proceedings of the ICCIMA 2005: Sixth International Conference on Computational Intelligence and Multimedia Applications*, (Las Vegas, NV: IEEE), 303–308.

Guillen, J., Garcia-Olivares, A., Ojeda, E., Osorio, A., Chic, O., and Gonzalez, R. (2008). Long-term quantification of beach users using video monitoring. *J. Coast. Res.* 24, 1612–1619. doi: 10.2112/07-0886.1

Harlan, J., Terrill, E., Hazard, L., Keen, C., Barrick, D., Whelan, C., et al. (2010). The integrated ocean observing system high-frequency radar network: status and local, regional, and national applications. *Mar. Technol. Soc. J.* 44, 122–132. doi: 10.4031/Mtsj.44.6.6

Harley, M. D., Andriolo, U., Armaroli, C., and Ciavola, P. (2014). Shoreline rotation and response to nourishment of a gravel embayed beach using a low-cost video monitoring technique: San Michele-Sassi Neri, Central Italy. *J. Coast. Conserv.* 18, 551–565. doi: 10.1007/s11852-013-0292-x

Herbers, T. H. C., and Guza, R. T. (1990). Estimation of directional wave spectra from multicomponent observations. *J. Phys. Oceanogr.* 20, 1703–1724. doi: 10.1175/1520-04851990020<1703:Eodwsf<2.0.Co;2

Hinkler, J., Pedersen, S. B., Rasch, M., and Hansen, B. U. (2002). Automatic snow cover monitoring at high temporal and spatial resolution, using images taken by a standard digital camera. *Int. J. Remote Sens.* 23, 4669–4682. doi: 10.1080/01431160110113881

Holland, K. T., Holman, R. A., Lippmann, T. C., Stanley, J., and Plant, N. (1997). Practical use of video imagery in nearshore oceanographic field studies. *IEEE J. Ocean. Eng.* 22, 81–92. doi: 10.1109/48.557542

Holland, K. T., Puleo, J. A., and Kooney, T. N. (2001). Quantification of swash flows using video-based particle image velocimetry. *Coast. Eng.* 44, 65–77. doi: 10.1016/S0378-3839(01)00022-29

Holland, K. T., Raubenheimer, B., Guza, R. T., and Holman, R. A. (1995). Runup kinematics on a natural beach. *J. Geophys. Res. Ocean* 100, 4985–4993. doi: 10.1029/94jc02664

Holman, R., and Haller, M. C. (2013). Remote Sensing of the Nearshore. *Ann. Rev. Mar. Sci.* 5 5, 95–113. doi: 10.1146/annurev-marine-121211-172408

Holman, R., Plant, N., and Holland, T. (2013). cBathy: a robust algorithm for estimating nearshore bathymetry. *J. Geophys. Res. Ocean* 118, 2595–2609. doi: 10.1002/jgrc.20199

Holman, R. A., and Guza, R. T. (1984). Measuring run-up on a natural beach. *Coast. Eng.* 8, 129–140. doi: 10.1016/0378-3839(84)90008-90005

Holman, R. A., and Stanley, J. (2007). The history and technical capabilities of Argus. *Coast. Eng.* 54, 477–491. doi: 10.1016/j.coastaleng.2007.01.003

Holman, R. A., Symonds, G., Thornton, E. B., and Ranasinghe, R. (2006). Rip spacing and persistence on an embayed beach. *J. Geophys. Res. Ocean* 111:C01006. doi: 10.1029/2005jc002965

IOOS (2016). *Manual for Real-Time Quality Control of High Frequency Radar Surface Current Data: A Guide to Quality Control and Quality Assurance of High Frequency Radar Surface Currents Data Observations*. Silver Spring, MD: U.S. Integrated Ocean Observing System.

Jimenez, J. A., Osorio, A., Marino-Tapia, I., Davidson, M., Medina, R., Kroon, A., et al. (2007). Beach recreation planning using video-derived coastal state indicators. *Coast. Eng.* 54, 507–521. doi: 10.1016/j.coastaleng.2007.01.012

Kako, S., Isobe, A., Kataoka, T., Yufu, K., Sugizono, S., Plybon, C., et al. (2018). Sequential webcam monitoring and modeling of marine debris abundance. *Mar. Pollut. Bull.* 132, 33–43. doi: 10.1016/j.marpolbul.2018.04.075

Kako, S., Isobe, A., and Magome, S. (2010). Sequential monitoring of beach litter using webcams. *Mar. Pollut. Bull.* 60, 775–779. doi: 10.1016/j.marpolbul.2010.03.009

Kataoka, T., Hinata, H., and Kako, S. (2012). A new technique for detecting colored macro plastic debris on beaches using webcam images and CIELUV. *Mar. Pollut. Bull.* 64, 1829–1836. doi: 10.1016/j.marpolbul.2012.06.006

Leeuw, T., and Boss, E. (2018). The hydrocolor app: above water measurements of remote sensing reflectance and turbidity using a smartphone camera. *Sensors* 18, E256. doi: 10.3390/s18010256

Lippmann, T. C., and Holman, R. A. (1989). Quantification of sand-bar morphology - a video technique based on wave dissipation. *J. Geophys. Res. Ocean* 94, 995–1011. doi: 10.1029/JC094iC01p00995

Long, J. W., and Ozkan-Haller, H. T. (2016). Forcing and variability of nonstationary rip currents. *J. Geophys. Res. Ocean* 121, 520–539. doi: 10.1002/2015jc010990

Mole, M. A., Mortlock, T. R. C., Turner, I. L., Goodwin, I. D., Splinter, K. D., and Short, A. D. (2013). Capitalizing on the surfcam phenomenon: a pilot study in regional-scale shoreline and inshore wave monitoring utilizing existing camera infrastructure. *J. Coast. Res.* 2, 1433–1438. doi: 10.2112/Si65-242.1

Nieto, M. A., Garau, B., Balle, S., Simarro, G., Zarruk, G. A., Ortiz, A., et al. (2010). An open source, low cost video-based coastal monitoring system. *Earth Surf. Process. Landf.* 35, 1712–1719. doi: 10.1002/esp.2025

Pearre, N. S., and Puleo, J. A. (2009). Quantifying seasonal shoreline variability at rehoboth beach, delaware, using automated imaging techniques. *J. Coast. Res.* 25, 900–914. doi: 10.2112/08-1029.1

Pianca, C., Holman, R., and Siegle, E. (2015). Shoreline variability from days to decades: results of long-term video imaging. *J. Geophys. Res. Ocean* 120, 2159–2178. doi: 10.1002/2014jc010329

Pitman, S., Gallop, S. L., Haigh, I. D., Mahmoodi, S., Masselink, G., and Ranasinghe, R. (2016). Synthetic imagery for the automated detection of rip currents. *J. Coast. Res.* 75, 912–916. doi: 10.2112/Si75-183.1

Plant, N. G., Aarninkhof, S. G. J., Turner, I. L., and Kingston, K. S. (2007). The performance of shoreline detection models applied to video imagery. *J. Coast. Res.* 23, 658–670. doi: 10.2112/1551-5036(2007)23%5B658:tposdm%5D2.0.co;2

Puleo, J. A., Farquharson, G., Frasier, S. J., and Holland, K. T. (2003). Comparison of optical and radar measurements of surf and swash zone velocity fields. *J. Geophys. Res. Ocean* 108:3100.

Richardson, A. D., Braswell, B. H., Hollinger, D. Y., Jenkins, J. P., and Ollinger, S. V. (2009). Near-surface remote sensing of spatial and temporal variation in canopy phenology. *Ecol. Appl.* 19, 1417–1428. doi: 10.1890/08-2022.1

Richardson, A. D., Jenkins, J. P., Braswell, B. H., Hollinger, D. Y., Ollinger, S. V., and Smith, M. L. (2007). Use of digital webcam images to track spring green-up in a deciduous broadleaf forest. *Oecologia* 152, 323–334. doi: 10.1007/s00442-006-0657-z

Roush, W., Munroe, J. S., and Fagre, D. B. (2007). Development of a spatial analysis metho using ground-based repeat photography to detect changes in the alpine treeline ecotone, Glacier National Park, Montana, USA. *Arctic Antarctic Alpine Res.* 39, 297–308. doi: 10.1657/1523-0430(2007)39%5B297:doasam%5D2.0.co;2

Shand, T. D., Bailey, D. G., and Shand, R. D. (2012). Automated detection of breaking wave height using an optical technique. *J. Coast. Res.* 28, 671–682. doi: 10.2112/Jcoastres-D-11-00105.1

Silva-Cavalcanti, J. S., Costa, M. F., and Pereira, P. S. (2018). Rip currents signaling and users behaviour at an overcrowded urban beach. *Ocean Coast. Manag.* 155, 90–97. doi: 10.1016/j.ocecoaman.2018.01.031

Sonnentag, O., Detto, M., Vargas, R., Ryu, Y., Runkle, B. R. K., Kelly, M., et al. (2011). Tracking the structural and functional development of a perennial pepperweed (Lepidium latifolium L.) infestation using a multi-year archive of webcam imagery and eddy covariance measurements. *Agric. For. Meteorol.* 151, 916–926. doi: 10.1016/j.agrformet.2011.02.011

Splinter, K. D., Strauss, D. R., and Tomlinson, R. B. (2011). Assessment of post-storm recovery of beaches using video imaging techniques: a case study at gold coast, Australia. *IEEE Trans. Geosci. Remote Sens.* 49, 4704–4716. doi: 10.1109/Tgrs.2011.2136351

Stockdon, H. F., and Holman, R. A. (2000). Estimation of wave phase speed and nearshore bathymetry from video imagery. *J. Geophys. Res. Ocean* 105, 22015–22033. doi: 10.1029/1999jc000124

Stockdon, H. F., Holman, R. A., Howd, P. A., and Sallenger, A. H. (2006). Empirical parameterization of setup, swash, and runup. *Coast. Eng.* 53, 573–588. doi: 10.1016/j.coastaleng.2005.12.005

Suanda, S. H., Barth, J. A., Holman, R. A., and Stanley, J. (2014). Shore-based video observations of nonlinear internal waves across the inner shelf. *J. Atmos. Ocean. Technol.* 31, 714–728. doi: 10.1175/Jtech-D-13-00098.1

Taborda, R., and Silva, A. (2012). COSMOS: a lightweight coastal video monitoring system. *Comput. Geosci.* 49, 248–255. doi: 10.1016/j.cageo.2012.07.013

Turner, I. L., Whyte, D., Ruessink, B. G., and Ranasinghe, R. (2007). Observations of rip spacing, persistence and mobility at a long, straight coastline. *Mar. Geol.* 236, 209–221. doi: 10.1016/j.margeo.2006.10.029

van Dongeren, A., Plant, N., Cohen, A., Roelvink, D., Haller, M. C., and Catalan, P. A. (2008). Beach wizard: nearshore bathymetry estimation through assimilation of model computations and remote observations. *Coast. Eng.* 55, 1016–1027. doi: 10.1016/j.coastaleng.2008.04.011

van Enckevort, I. M. J., and Ruessink, B. G. (2003). Video observations of nearshore bar behaviour. *Part* 1: alongshore uniform variability. *Cont. Shelf Res.* 23, 501–512. doi: 10.1016/S0278-4343(02)00234-230

Wilson, G. W., Ozkan-Haller, H. T., Holman, R. A., Haller, M. C., Honegger, D. A., and Chickadel, C. C. (2014). Surf zone bathymetry and circulation predictions via data assimilation of remote sensing observations. *J. Geophys. Res. Ocean* 119, 1993–2016. doi: 10.1002/2013jc009213

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frontiers in Marine Science

REVIEW
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Coastal Ocean and Nearshore Observation: A French Case Study

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To understand and predict the physical, chemical, and biological processes at play in coastal and nearshore marine areas requires an integrated, interdisciplinary approach. The case study of the French structuration of coastal ocean and nearshore observing systems provides an original overview on a federative research infrastructure named ILICO. It is a notable example of national structuration and pan-institution efforts to investigate the forefront of knowledge on the processes at work within the critical coastal zone. ILICO comprises, in a pluridisciplinary approach, eight distributed network-systems of observation and data analysis that are accredited and financially supported by French research institutions and the French Ministry for Higher Education, Research, and Innovation. ILICO observation points are implemented along metropolitan and overseas French coasts, where coastline dynamics, sea level evolution, physical and biogeochemical water properties, coastal water dynamics, phytoplankton composition, and health of coral reefs are monitored in order to address a wide range of scientific questions. To give an overview of the diversity and potential of the observations carried out, this paper offers a detailed presentation of three constituting networks: Service Observation en Milieu LITtoral (SOMLIT), with homogeneous sampling strategies, DYNALIT, with heterogeneous sampling strategies adapted to different environments, and Mediterranean Ocean Observing System for the Environment (MOOSE), an integrated, pluri-disciplinary coastal/offshore regional observatory in the north-western Mediterranean Sea. ILICO was conceived using a European framework. It addresses the great challenges of the next decade in terms of sustainability, cost-efficiency, interoperability, and innovation. This paper emphasizes the added-value of federating these systems, and highlights some recommendations for the future.

Keywords: observation infrastructure, national structuration, interdisciplinary, coastal ocean, coastline

INTRODUCTION – CHALLENGES AND MOTIVATIONS OF AN INTEGRATED COASTAL OCEAN AND NEARSHORE OBSERVATORY

The coastal ocean and nearshore zones are complex areas featuring diverse bio-physico-geomorphological environments, rich in potential scientific knowledge and exposed to numerous strategical economic and ecological stakes. Multiple definitions of coastal systems can be found among the Ocean observation bibliography (Davis and Ethington, 1976; Lorenzoni and Benway, 2013; Baschek et al., 2017; Petihakis et al., 2018). This paper considers the nearshore zone as the area where land and water join to create an environment with a distinct structure, diversity, and flow of energy.

Being a transitional space directly subject to anthropic activities, the nearshore area is subject to multiple forcings at various spatial and temporal scales. Its evolution raises various scientific issues, which are meant to be addressed by the integrated observation system described in this paper:

- Understanding the physical, chemical, and biological processes at work in the systems general dynamics.
- Characterizing and understanding the long-term changes of these systems and the specific role of climate change in the process.
- Understanding and quantifying the specific and cumulative impacts of local anthropogenic pressures, while disentangling them from the natural evolution processes at the same scales.
- Characterizing and understanding the rare and extreme events impacting the coastal and nearshore systems, and the resilience processes after these events.
- Improving and optimizing the already existing observation networks, together with developing methods for scale transfer.

In order to understand and predict the physical, chemical, and biological processes controlling these areas, the observation of coastal and nearshore ecosystems thus requires:

- An integrated and multidisciplinary approach (example given: a wide range of parameters mixing biological and physico-chemical properties).
- Observation sites and parameters robust enough to characterize the global evolution trends of many different coastal environments at many different time scales (e.g., diffuse and long-term changes as well as adverse consequences of extreme events).
- To take full advantage of both remote and multiple *in situ* techniques (from high frequency sensors to low frequency measurement campaigns) to describe a given environment.

In addition, with references to integrated systems already developed in several coastal regions (e.g., IOOS – U.S. Integrated Ocean Observing System, IMOS – Integrated Marine Observing System, COSYNA – Baschek et al., 2017, POSEIDON – Petihakis et al., 2018), this diverse and ambitious instrumental facility also calls for:

- The implementation of coastal observation into larger scale ocean observing systems to foster the understanding and forecasting of the evolution of global ocean and anthropized nearshore zones.
- An optimal balance between the sampling of targeted regions with ocean observatories, up-to-date modeling capacities and end-user requirements.

Lastly, this approach of long-term nearshore and littoral observing systems tends to transcend academic research boundaries and significantly contribute to (i) education (academic curriculums, lifelong learning programs, outreach activities, (ii) industrial need, and (iii) public policy support (scientific mediation, coastal risk assessment, and adaptive management).

THE FRENCH COASTAL OCEAN AND NEARSHORE OBSERVATION STRUCTURATION

From Local to National Integrated Systems

Since the 1980s, according to their missions and their geographical location, certain French science-oriented public institutions have created, developed, and structured coastal observatories along metropolitan and oversea coastlines. These institutions are: CNRS-INSU: National Center for Scientific Research – National Institute for Earth Sciences and Astronomy[1]/Ifremer: French Research Institute for Exploitation of the sea[2]/IRD: National Research Institute for Sustainable Development[3]/Shom: Naval Hydrographic and Oceanographic Service[4]/IGN: National Geographic Institute[5] and several French Marine Universities[6].

During the 1990's, CNRS-INSU designed 5-year-long National Observation Services (SNO) accreditations to federate thematically observation facilities (tools, resources, services) dedicated to earth observation. Such accredited services are motivated by the need to document the long-term changes, evolution, and variability of terrestrial systems, and to advance knowledge in these areas. Decisions to create new SNO, and to renew, evolve or abolish existing SNO, are based on a scientific evaluation organized by specialized committees including scientific experts from each French public institution with an interest in scientific observation.

SNO are provided with recurrent catalytic funding, and in return are intended to provide some services to the scientific

[1] http://www.insu.cnrs.fr
[2] wwz.ifremer.fr/en
[3] en.ird.fr/the-ird
[4] www.shom.fr/en/
[5] www.ign.fr/institut/en
[6] https://www.universites-marines.fr/fr

community for production and access to data. They have an obligation to implement the necessary processes to share data and metadata without any retention conditions (within the constraints imposed by international organizations).

This accreditation became a recognized label for observation structuration, leading to applications from observation teams outside the CNRS, and thus paving the way for national structuration.

ILICO – The French Research Infrastructure for Coastal Oceans and Seashores

In 2014, with the intention of fostering the structuration of the landscape of resources dedicated to research of a national scope (measurement tools, observation, modeling, simulations, etc.), the French Ministry of Higher Education, Research, and Innovation (MESRI) offered to federate the coastal, nearshore, and littoral observation services (**Figure 1** and **Table 1**) and research communities within a national research infrastructure named ILICO (Infrastructure de Recherche Littorale et Côtière[7]). ILICO is one of the 99 research infrastructures which cover the entire spectrum of French research. Research infrastructures are strategic steering tools which aim to structure initiatives and investments made in the field of research.

The ILICO research infrastructure is dedicated to the knowledge of natural coastal and nearshore system dynamics. It mobilizes approximately 420 employees corresponding to 90 full-time positions, and has a total annual budget (including salaries) of approximately 10 M€.

ILICO observation points (**Figures 2A,B**) are implemented along metropolitan and overseas French coasts, and monitor coastline dynamics, sea level evolution, physical and biogeochemical water properties, coastal water dynamics, phytoplankton composition, and the health of benthic habitats.

ILICO networks utilize a wide range of observation techniques (**Figure 3** and **Table 1**).

[7] www.ir-ilico.fr

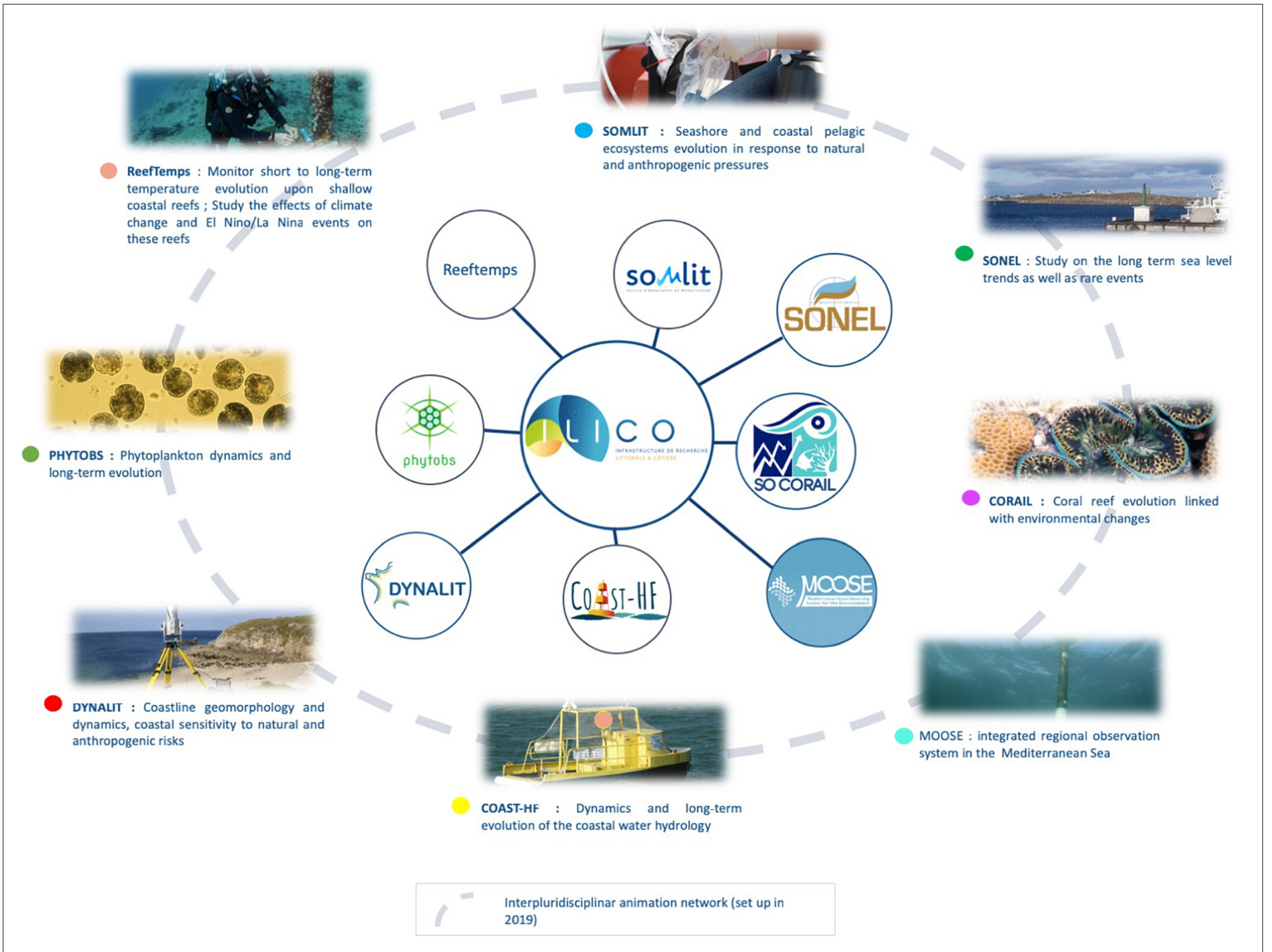

FIGURE 1 | ILICO networks.

TABLE 1 | Presentation of ILICO eight observation networks.

Network (creation date)	Measurement strategy			Scientific outcomes/rationale
	Parameters	**Observation spots**	**Frequency**	
COAST-HF (2016)	Conductivity/salinity; wave direction, velocity and periodicity; wind direction and velocity; fluorescence; dissolved oxygen; pH; turbidity; nutrients; atmospheric pressure and humidity; aerial and water temperature	Fourteen high frequency, permanent, observation platforms along the French coast	The sampling frequency is adapted to each of the parameters (e.g., 10–30 min for the physical parameters; once a day for the nutrients)	By federating and managing high frequency, continuous observation platforms along the French coasts, COAST-HF contributes to the monitoring and understanding of physics–biology multi-scale coupling and to detecting some extreme episodic events not detected by a lower resolution (1- or 2-weeks sampling intervals) monitoring approach (Blain et al., 2004; Many et al., 2016)
CORAIL (1985)	Coral reef communities: Abundance, age, biomass, taxonomic diversity, mortality, habitat structure, population structure, demographic features. Physico-chemical environment: fluorimetry, nutrients, dissolved oxygen, pH, chlorophyll *a*, water pressure, salinity, temperature, turbidity.	Captures physical, physico-chemical, and biological evolution in time in coral reef ecosystem	For the biological parameters the sampling frequency is once a year or once every 2 years. For the physical parameters, between one and four times per hour with automatic systems.	CORAIL long-term monitoring captures the evolution of the ecological properties of coral reef ecosystems of the tropical South Pacific area, as well as associated physico-chemical parameters. It aims to detect, follow, analyze, and model the coral reefs evolution linked with environmental changes induced by human activities and climate change (Galzin et al., 2015; Lamy et al., 2016)
DYNALIT (2014)	Nearshore bathymetry and topography, shoreline position, pictures of the seashore, turbidity, wave characteristics, currents.	Thirty-five coastal sites in metropolitan and oversea France covering a wide range of geomorphology (littoral systems, open bays, ria, estuary, lagoon, semi-enclosed systems, etc.), and characteristics: oligo/eutrophic ecosystems, micro/mega-tidal regimes, etc.	Measure frequency: from 5 to 10 min for high frequency and from one to two times per year for low frequency	To analyze the coastal geomorphological sensitivity to natural and anthropogenic risks, DYNALIT allows observation and quantification of the seashore evolution, and understanding of the morphodynamical processes. (see section "DYNALIT Network")
MOOSE (2008)	Cf. **Table 2**	Cf. **Table 2**	Cf. **Table 2**	Over the last decades long-term warming and increasing salinity trends have been established in the North-West Mediterranean Sea (Rohling and Bryden, 1992; Béthoux and Tailliez, 1994; Krahmann and Schott, 1998; Send et al., 1999; Béthoux et al., 2002; Rixen et al., 2005). Due to the complexity of the phenomenon at various temporal and spatial scales and its impacts on biogeochemical content (e.g., nutrients replenishment, carbon uptake), only long-term continuous observations are able to improve our knowledge on the temporal variability of the northwestern Mediterranean water changes (Somot et al., 2016) (see section "The MOOSE Network")
PHYTOBS (2016)	Phytoplankton diversity and abundance (micro-phytoplankton, and in some places nano and pico) dissolved oxygen, pH, temperature, salinity, turbidity, pigment, chlorophyll	Twenty-six observation sites along the French metropolitan coasts	The frequency of the measurements is two times per month	Long-term series on marine phytoplankton and related hydrological conditions are not only of interest in the study of phytoplankton population and community dynamics, but also on the impact of climate change on marine biodiversity (Widdicombe et al., 2010; Wiltshire et al., 2010; Hernández-Fariñas et al., 2014). PHYTOBS observations along French metropolitan coasts detected significant temporal changes in phytoplankton communities (Rombouts et al., 2019) and also contributed to highlight different environmental controls that might favor the bloom developments (Thorel et al., 2017)

(Continued)

TABLE 1 | Continued

Network (creation date)	Measurement strategy			Scientific outcomes/rationale
	Parameters	**Observation spots**	**Frequency**	
REEFTEMPS (2010)	Temperature, pressure, and sometimes pH, chlorophyll, salinity, waves, dissolved oxygen, turbidity	Network of temperature (and sometimes multiparameter) sensors in the coral reefs of the South Pacific Ocean; 75 observation sites deployed in 20 countries Depth: from 6 to 60 m	Temperature frequency from 1 to 30 min according the sites Other parameters: 15–30 min	REEFTEMPS temperature data series in the coral reefs of the Pacific Ocean are open to a wide scientific community, they may be used (i) to monitor the long-term effects of climate change and El Niño/La Niña events and their impacts on the coral reefs and associated resources, (ii) to characterize coastal upwelling, circulation, and heat balance along coral reefs, in relation to wind stress or local biological or thermal structures (Alory et al., 2006; Marchesiello et al., 2010); or (iii) to help to validate lagoon models or numerical simulations (Ouillon et al., 2005)
SOMLIT (1996)	Nutrients, dissolved oxygen, pH, temperature,suspended particulate matter, turbidity, fluorescence, chlorophyll, salinity, particulate organic carbon, and nitrogen, δ^{15}N, δ^{13}C, determination, numbering, and optical properties of pico- and nanoplankton classes.	19 observation sites located in 11 ecosystems dispatched on the French coast	The frequency of the measurements is two times per month	The SOMLIT network measures a wide range of hydrological and biogeochemical characteristics of the surface waters once every 2 weeks. It is presented in more detail thereafter (see section "SOMLIT Network")
SONEL (2003)	Sea level, leveling height, geocentric height, intensity of gravity field, geodetic positioning	Eighty-six measurement sites along metropolitan French coasts and overseas	Daily and monthly mean sea level for Tide Gauges and 30 sec for the co-located GNSS stations	SONEL provides high-quality continuous measurements of sea- and land levels at the coast from tidal gauges (relative sea levels) and from GNSS geodetic techniques (vertical land motion and absolute sea levels) for studies on long-term sea level trends as well as rare events. Initially designed for maritime navigation purposes, some of the oldest tide gauge records date back to the 18th century (e.g., Woppelmann et al., 2006). Data archeology have successfully recovered sea-level information valuable for climate studies (Testut et al., 2006; Pouvreau, 2008)

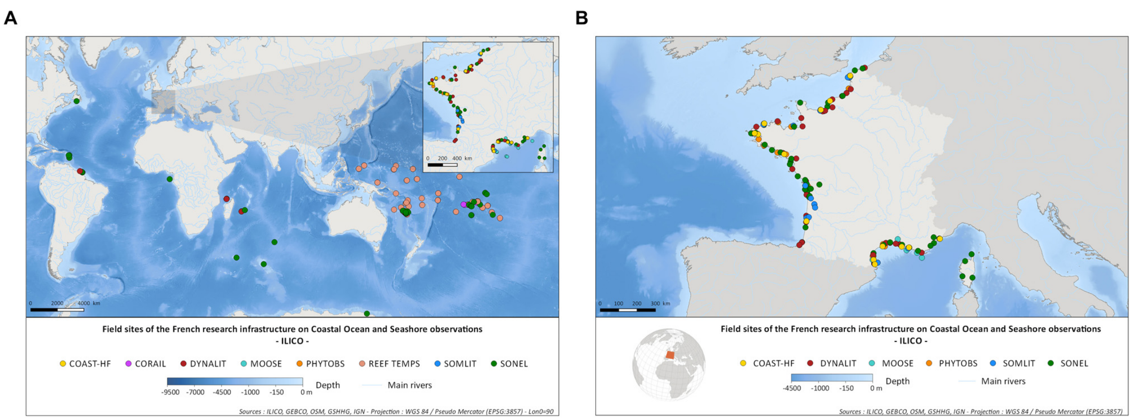

FIGURE 2 | (A) Global fields sites of ILICO observation. **(B)** Metropolitan fields sites of ILICO observation.

In order to meet the ambitious motivations and challenges, ILICO (started in 2016) inherited a great number of facilities and organizations, some of which were built over decades.

In addition to these observation networks, ILICO runs a scientific transversal network in charge of general scientific potential and of optimizing the use of data in high-level research projects.

FIGURE 3 | Techniques used for coastal ocean and nearshore observation.

Observation networks, mainly pre-existing ILICO for years, have combined their unique viewpoints and strengths in order to examine the global strategy. In this paper, we would like to highlight the contributions of three networks, given their particular characteristics: (i) SOMLIT, with a homogeneous sampling strategy, (ii) DYNALIT, challenged with its heterogenous observation sites in terms of physiographic conditions and monitoring strategies, and (iii) Mediterranean Ocean Observing System for the Environment (MOOSE), laying the groundwork for an integrated observation network.

SOMLIT Network

Scientific Objectives

SOMLIT (Coastal ocean observation service – Service Observation en Milieu LITtoral) studies the long-term evolution of coastal pelagic ecosystems and seeks to determine the natural and anthropic driving mechanisms of their functioning at local and regional scales. It focuses on the hydrological, biogeochemical, and ecological characteristics of the surface waters. It also aims at providing data sets to national and international communities for research, education, and stakeholder purposes, and serves as logistic support for research and education projects.

Short Description of the Observation Network

Gathering six marine stations and laboratories at its creation in 1996, SOMLIT now observes 11 ecosystems distributed along the English Channel, the Bay of Biscay, and the Mediterranean Sea. These ecosystems cover a large range of characteristics, such as trophic status (from oligo- to eutrophic ecosystems), tidal regime (from micro- to mega-tidal regimes), geomorphology (littoral systems, open bays, ria, estuary, lagoon, semi-enclosed systems, etc.), connection to the continent, and turbidity, etc. Each ecosystem is studied thanks to one, two, or three sampling sites, with a total of 19 sites sampled along a continent-ocean gradient (when more than one site is sampled per ecosystem) (**Figure 4**). Sixteen parameters [temperature, salinity, pH, dissolved oxygen, nitrate, nitrite, ammonium, phosphate, dissolved silica, suspended particulate matter (SPM), particulate organic carbon (POC), and nitrogen (PN) and their isotopic composition ($\delta^{13}C_{POC}$, $\delta^{15}N_{PN}$), chlorophyll *a*, and pico- and nano-plankton (determination, numbering, and optical properties of plankton classes)] are measured *in situ* or after water sampling and processing on a bi-monthly basis using standardized protocols and under quality control. In addition, water column profiles of temperature, salinity, and fluorescence are performed. More than 80 people from 13 research units belonging to 12 institutions are involved in SOMLIT.

More than 80 persons representing fifteen Full-Time Equivalent (FTE) from 12 institutions (CNRS, marine universities, etc.) and 13 research units are involved in the SOMLIT.

Some Key Scientific Results

First of all, it appears that the ecosystems studied by SOMLIT are deeply sensitive to climate variability. Indeed, a study focused on the first 10 years of the SOMLIT data sets (1997–2006; Goberville et al., 2010) revealed strong correlations between regional climate and hydro-climatic characteristics (sea level pressure, wind direction and intensity, sea surface temperature, and precipitation), the coastal environment (i.e., SOMLIT historical parameters: temperature, salinity, pH, dissolved oxygen, nutrients, SPM, POC, PN, and chlorophyll *a*) and two large-scale climate indexes – the Northern Hemisphere Temperature (NHT) and the Atlantic Multi-decadal Oscillation (AMO). A similar study (Lheureux et al., in preparation) performed on data sets covering two decades confirms this tight coupling between coastal environment, hydro-climatic characteristics, and climate indexes including the AMO and NHT, but also the NAO (Northern Atlantic Oscillation) and EAP (Eastern Atlantic Pattern) as well as river characteristics (flow, nutrient concentrations).

A study dedicated to POC and PN concentrations and stoichiometry compared temporal (from infra-seasonal to decadal) variability among coastal (mainly SOMLIT) and open-ocean sites and ecosystems (Talarmin et al., 2016). An overall discrimination appeared between coastal and open-ocean sites. Coastal waters usually encountered a higher seasonal variability of POC and PN concentrations and ratios as compared to open-ocean sites, and exhibited declines in POC and PN concentrations. However, (i) there were numerous local particularities, and (ii) short-term (i.e., infra-seasonal) variability was a large fraction of the temporal variability. This may highlight the role of local conditions in the variability of POC and PN concentration and stoichiometry.

A study (Liénart et al., 2017, 2018) dedicated to the origin and composition of particulate organic matter (POM) highlighted the high dominance of phytoplankton in the POM composition in the SOMLIT ecosystems, except in the Gironde estuary in which POM is mainly of terrestrial origin. Two main gradients were revealed. First, a continent-ocean gradient with offshore sites where POM is almost

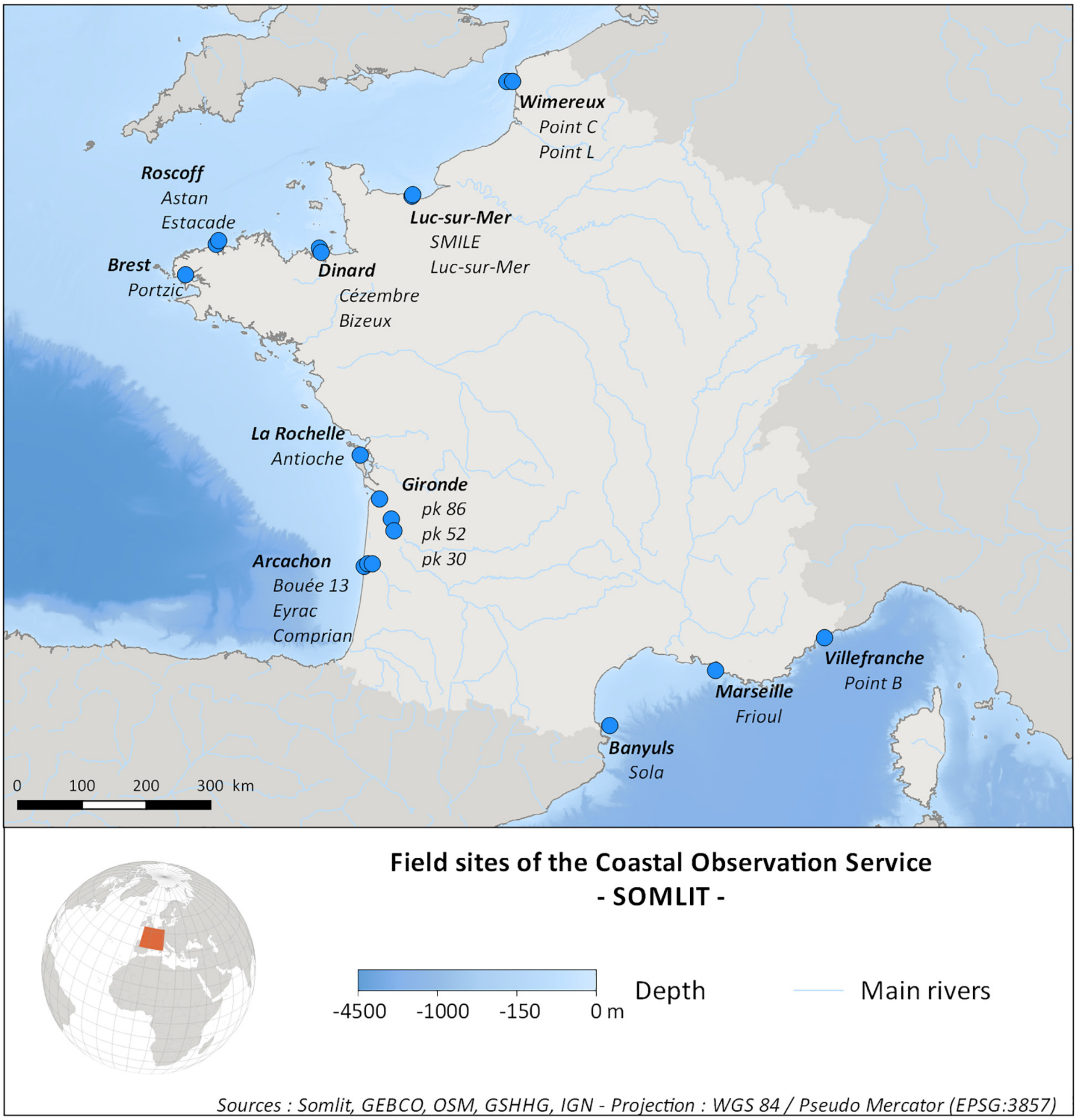

FIGURE 4 | Location of the SOMLIT sampling sites along the French metropolitan coasts.

only composed of marine phytoplankton, versus sites located close to the continent in shallower water columns where the contribution of benthic POM (seagrasses, benthic micro- and macro-algae) and/or continental POM (riverine/estuarine phytoplankton and terrestrial POM) is noticeable. Second, a gradient of ecosystem trophic-status where the POM compositions of oligotrophic ecosystems are characterized by the presence of diazotrophs. Hydrodynamics, sedimentary dynamics, and depth of the water column are the drivers of the POM composition along the former gradient, whereas nutrient availability is the main driver along the latter gradient.

Discussion

During the last two decades, SOMLIT has evolved in three directions. (1) The number of monitored ecosystems and sites has increased: Firstly, the number of study sites per ecosystem increased for some ecosystems (e.g., the Arcachon lagoon) in order to better take into account the onshore-offshore gradient for the long-term evolution of the coastal ecosystems; as well, more research teams and units joined the SOMLIT network allowing for the monitoring of a larger group and larger types of ecosystems (e.g., the bay of Seine, a large open bay). The challenge here is to develop and promote standardized protocols easily transferable to a wider community. (2) The number of parameters increased beyond the traditional ocean hydrology parameters; notably, stable isotope ratios of POC and PN enable researchers to take into account the large diversity of POM sources, which is specific to the coastal ocean, considering that the different sources of POM do not behave similarly regarding biogeochemical cycles and trophic transfer; also the determination and counting of pico- and nano-plankton classes allow researchers to take into account the plankton diversity, which is deeply linked with biogeochemical cycles. (3) The scientific use of the SOMLIT data sets evolved from local studies to national and international studies (e.g., the results cited above). These three directions should be maintained over the next decade and promoted within ILICO, along with robust statistic tools.

DYNALIT Network

Scientific Objectives

The primary scientific objective of SNO DYNALIT is to collect relevant, long-term, and accurate data on the physical evolution of the coast. DYNALIT aims to increase our understanding and predictive capability of coastal dynamics, in the context of increased coastal urbanization and threats by climate change, through the development of innovative numerical models. An overarching goal of DYNALIT is to support evidence-based policies and contribute to sustainable coastal risk management in the regions threatened by erosion and submersion hazards.

Short Description of the Observation Network

SNO DYNALIT, accredited by CNRS-INSU, was established in 2014 to monitor coastal change and the primary factors at play along tropical overseas and temperate metropolitan French waters. At the time of writing this paper, DYNALIT includes more than 120 researchers from 20 laboratories and 22 universities. Observations are collected at 35 coastal sites in metropolitan and oversea France (**Figure 5**), encompassing the three main coastal environments, namely sandy, rocky, and muddy coasts, including, e.g., open coasts, embayments, sandpits, and estuaries, with a wide spectrum of behaviors and of erosion/accretion trends. Observed parameters are primarily Digital Elevation Models (DEMs) on sandy and rocky coasts, and turbidity in estuarine environments. DEM data are collected through various means, including differential global positioning system measurements, video monitoring, structure from motion using unmanned aerial vehicles, and Lidar, while turbidity is typically measured *in situ* using turbidity meters. DYNALIT also collects additional environmental *in situ* and remotely sensed data such as shoreline position and links them with forcing factors such as incident waves, tide, and wind conditions.

Some Key Scientific Results

Climate change may cause an increase in coastal extreme events in many regions of the world (e.g., Zappa et al., 2013). In addition, rising sea levels will increase the occurrence of extreme water levels at the coast. Therefore, addressing the impact of extreme events and if and how the coast can recover is of paramount importance to improving models of flooding, erosion, and recovery and ultimately to assess coastal resilience. Addressing such short- to long-term impacts on the coast can only be achieved if long-term monitoring programs are operating on a representative range of coastal settings. A relevant example is the research that was driven by the winter of 2013/2014 during which an exceptional sequence of extratropical storms crossed the Northeast Atlantic region (Davies, 2015). According to numerical weather and wave hindcasts, that winter was the most energetic one along the Atlantic coast of Europe since at least 1948 (Masselink et al., 2016), and most of western Europe's sandy and rocky coastline was severely impacted (Castelle et al., 2015; Masselink et al., 2015; Autret et al., 2016; Burvingt et al., 2018). Masselink et al. (2016) analyzed a unique dataset of decadal, at least bimonthly surveyed, beach morphological changes along the west coast of Europe comprising sites from DYNALIT, namely Vougot, Porsmilin, and Truc Vert. The authors showed that while extensive beach and dune erosion occurred on open coasts due to offshore sediment transport, more sheltered sites experienced less erosion and one of the sites even experienced accretion due to beach rotation induced by alongshore sediment transport. Extending the same dataset to 2018, Dodet et al. (2019) showed that the recovery signature is site specific and multi-annual, with one studied beach fully recovered after 2 years, and the others only partially recovered after 4 years. On open cross-shore transport dominated coasts, simple semi-empirical shoreline change models (e.g., Yates et al., 2009; Splinter et al., 2014; Lemos et al., 2018) accurately reproduce the erosion driven by the 2013/2014 winter and subsequent post-storm recovery, but they largely fail on more complex sites. This further strengthens the recent development of a new generation of reduced-complexity shoreline change models coupling cross-shore, longshore, and other processes such as sea level rise (Vitousek et al., 2017; Robinet et al., 2018), to be used to investigate, hindcast, and ultimately forecast the erosion and recovery process in more detail on a wide range of coasts.

This demonstrates that implementing monitoring programs across a wide range of representative sites with different geological settings and degrees of wave exposure, as DYNALIT does, is crucial to understand and further predict the full natural variety of coastal response and recovery. Not only do the above studies improve our understanding of storm impact and subsequent recovery, which timing and magnitude can provide a proxy measure for coastal resilience to climatic variability and change, they also motivated new research into the winter wave climate and resulting multi-decadal change in winter mean, variability, and periodicity of wave activity in the North Atlantic Ocean (Castelle et al., 2017, 2018). The strong control of certain climate indices on winter wave climate and coastal response, such as the winter NAO and the West Europe Pressure Anomaly (WEPA) north and south of approximately 52°N, respectively, suggests that the ability of climate models to predict the winter NAO and WEPA indices a few months ahead will be crucial to anticipate coastal hazards along the Atlantic coast of Europe.

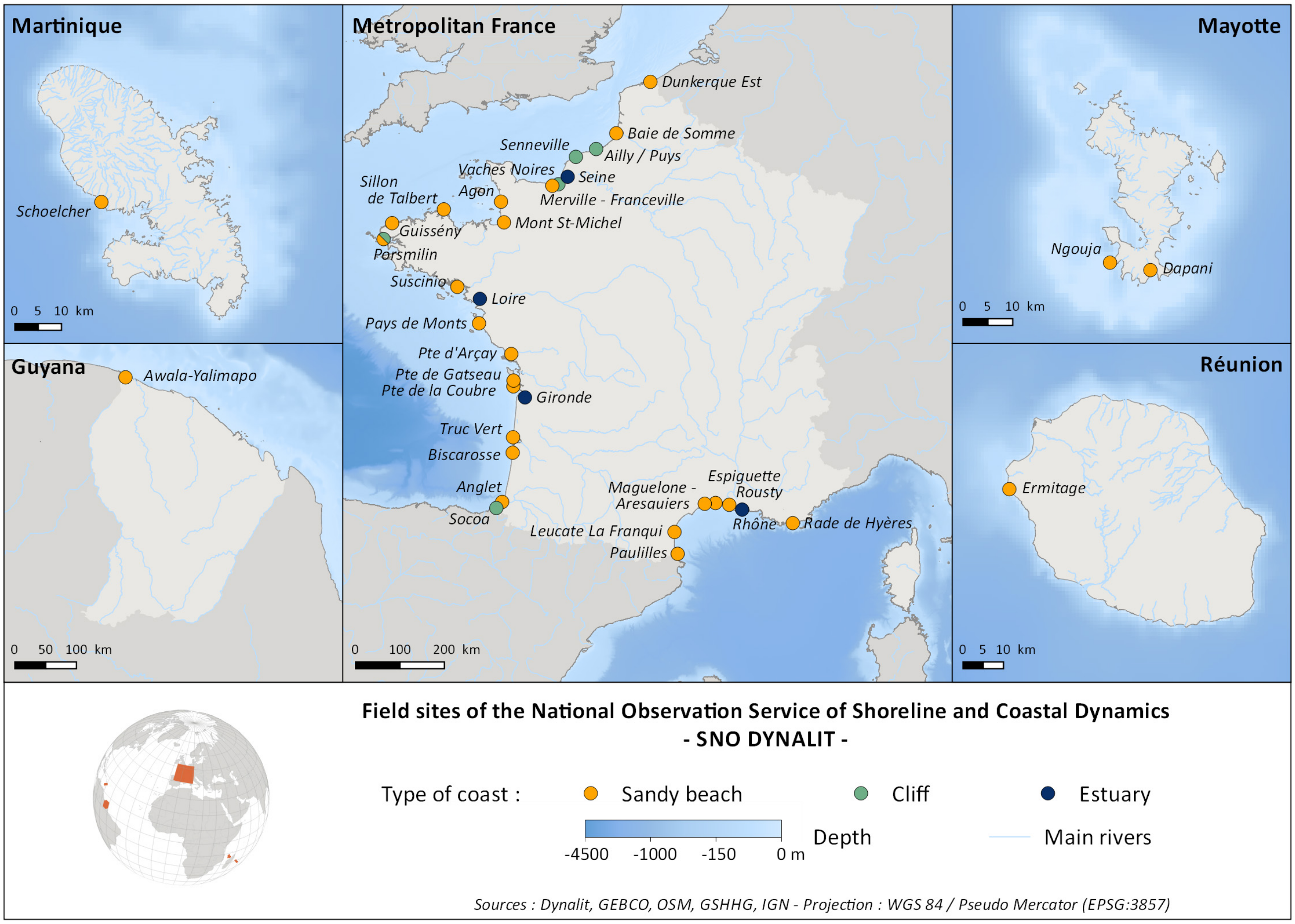

FIGURE 5 | Location map of the DYNALIT sites in metropolitan and overseas France with indication of the type of coasts.

Discussion

DYNALIT was established only 4 years ago and, except the recent studies discussed above and some common methodological developments in estuarine monitoring that were not addressed here, there has been only a little interaction and/or combination of data acquired at different sites with DYNALIT. Over the next few years, similarly to ILICO, DYNALIT will have to further encourage and develop inter-site collaborations and homogenize its monitoring strategies in order to perform more comprehensive studies on coastal response, such as that of Dodet et al. (2019). As a first step, DYNALIT is currently preparing a special issue for the Journal of Coastal Research, entitled « Coastal Evolution under Climate Change along the Tropical Overseas and Temperate Metropolitan France » in which a first synthesis of the DYNALIT monitoring programs and guidelines will be proposed. Within the next few years DYNALIT will also benefit from new means of surveying the coast. Some examples include the use of: (i) bathymetric Lidar, as while most of the DYNALIT surveys are performed dry on the intertidal domain, the subtidal domain hosts the largest sources of morphological variability, particularly along sandy coasts; (ii) satellite remote sensing which can now provide increasingly high resolution products to map the shoreline, and potentially infer the nearshore bathymetry, on large spatial scales which may close the gaps between the more precise but interspersed monitoring sites of DYNALIT. Lastly, more interactions between data and models must also be encouraged.

The MOOSE Network

Scientific Objectives

Slow and irreversible changes are occurring in Mediterranean waters – including the warming of deep waters, an increase in anthropogenic carbon dioxide, and acidification. Such factors are inducing changes in both deep waters and marine habitats as a whole. Despite intensive research efforts undertaken in the Mediterranean Sea over more than a century, an integrated view of its evolution, in the framework of climate change and anthropogenic pressures is still lacking. In this context, the Mediterranean Ocean Observing System for the Environment (MOOSE) has been set up as an interactive, distributed, and integrated observatory of the North-Western Mediterranean Sea to detect and identify long-term environmental anomalies. It includes both long-term monitoring and near real-time measurement capabilities concerning river inputs, atmospheric deposition, and *in situ* marine measurement capabilities.

Short Description of the Observation Network

The MOOSE Network was initiated in 2008 and built during the five following years. Since 2015 this organization has developed into a unique multidisciplinary network (**Figure 6**) that pools efforts and initiatives to converge on best practices, and supports common measurement standards (**Figure 7**).

The personnel assigned to these operations represent five FTE posts for researchers and 7.6 FTE posts for engineers and come from 10 different research institutions. Around 5–10 Ph.D. students have been regularly involved in the processing and analysis of data from the MOOSE network.

MOOSE is built as an interactive, distributed, and integrated observatory, based on a multisite network of permanent continental, shelf, shelf-break, and deep-sea stations, and is able to detect and monitor seasonal and inter-annual variability, as well as the impact of extreme events that control fluxes and budgets in the marine environment. It combines Eulerian observatories (moorings, radars, hydrological stations) and autonomous mobile platforms (gliders, profiling floats). The MOOSE network aims to acquire and provide the Essential Ocean Variables – EOV necessary to observe the variability of physical–biogeochemical and biological processes sensitive to climate change and anthropogenic pressure (**Table 2** and **Figure 7**).

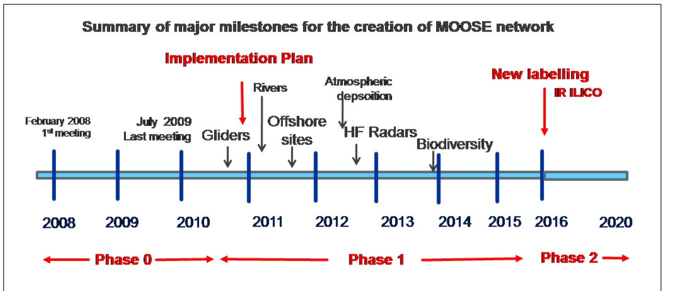

FIGURE 7 | Summary of major milestones and MOOSE phases.

The approach developed here aims to be more innovative compared to the last decade of programs being more focused on biogeochemistry and natural variability rather than on ecosystems, biodiversity and anthropogenic change.

Some Key Scientific Results

First, information on water mass distribution and deep water formation during winter has been collected using both the glider endurance lines and Eulerian moorings. The most important results concern the mesoscale circulation of the northern gyre, with a better characterization of (1) the variability of deep water formation processes (Houpert et al., 2015), (2) sub-mesoscale processes (Bosse et al., 2015, 2016; Damien et al., 2017),

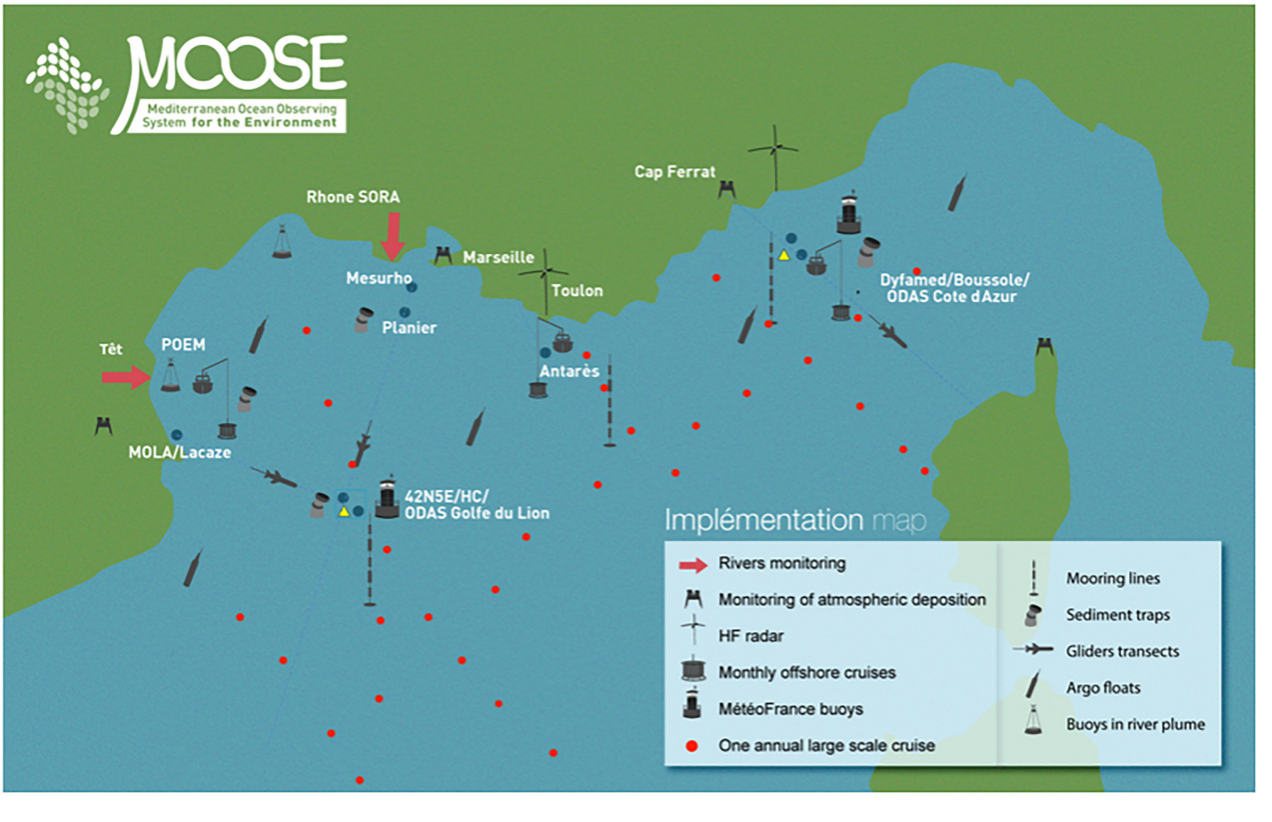

FIGURE 6 | Implementation map of the MOOSE network.

TABLE 2 | List of platforms and parameters involved in the MOOSE network.

	Platforms	Strategy	Parameters	Sampling frequency	Data transfer
Lagrangian marine monitoring	Gliders	Two transects T00 Nice-Calvi T02 Marseille-42°N	Temperature, salinity, oxygen, fluorescence, turbidity	Nine transects/year	Real time and delayed time
	HF Radars	Two radars Toulon Nice	Surface current – wave	Hourly measurements	Real time and delayed time
Eulerian marine monitoring	Mooring LIONCEAU	0–2,500 m	Temperature, salinity, oxygen, current	Hourly measurements	Delayed time
	Mooring DYFAMED	0–2,500 m	Temperature, salinity, oxygen, current, particle flux (mass, carbon, nitrogen)	Hourly measurements	Delayed time
	Mooring LION	0–2,500 m	Temperature, salinity, oxygen, current, particle flux (mass, carbon, nitrogen)	Hourly measurements	Delayed time
	Mooring Laccase-Duthiers	0–2,500 m	Temperature, salinity, oxygen, current, particle flux (mass, carbon, nitrogen)	Hourly measurements	Delayed time
	Mooring Planier	0–1,000 m	Temperature, salinity, oxygen, current, particle flux (mass, carbon, nitrogen)	Hourly measurements	Delayed time
	DYFAMED: research vessel – CTD-water collection – plankton net	One oceanic site 0–2,500 m	Temperature, salinity, oxygen, Underwater Video Profiler, nutrients, CO2, flow cytometer, phyto and zoo communities	Monthly cruises	Real time and delayed time
	ANTARES: MOLA: research vessel – CTD-water collection – plankton net	One oceanic site 0–2,500 m	Temperature, salinity, oxygen, Underwater Video Profiler, nutrients, CO_2, flow cytometer, phyto and zoo communities	Monthly cruises	Real time and delayed time
	MOLA: research vessel – CTD-water collection – plankton net	One oceanic site 0–2,500 m	Temperature, salinity, oxygen, nutrients, CO_2, flow cytometer	Annual cruises	Real time and delayed time
	MOOSE-GE: research vessel – CTD-water collection – plankton net	One oceanic site 0–2,500 m	Temperature, salinity, oxygen, CO_2, nutrients, flow cytometer, pigments	Monthly cruises, real time and delayed time	Real time and delayed time
Monitoring at the atmosphere/continent/sea interfaces	Rhone river	One site	Flow rate, suspended matter, organic and inorganic nutrients, trace metal	Daily collection	Delayed time
	Têt river	One site	Flow rate, suspended matter, organic and inorganic nutrients, trace metal	Daily collection	Delayed time
	Cap Ferrat (atmospheric deposition)	One site	Particle flux, organic and inorganic nutrients, trace metal, meteorology	Deposition: 2/month Rain event	Delayed time
	Frioul (atmospheric deposition)	One site	Particle flux, organic and inorganic nutrients, trace metal, meteorology	Deposition: 2/month Rain event	Delayed time
	Cap Béar (atmospheric deposition)	One site	Particle flux, organic and inorganic nutrients, trace metal, meteorology	Deposition: 2/month Rain event	Delayed time

and (3) quantification of shelf-slope mass balance exchanges (Durrieu de Madron et al., 2013).

New information on the dissolved oxygen variability in the North-Western Mediterranean Sea has been obtained, predicting that the lower intensity of winter convection could potentially lead to hypoxia in intermediate and deep layers with a substantial impact on marine ecosystems (Coppola et al., 2018).

High resolution sampling in the Rhone and Têt rivers, with monthly and high-resolution flood sampling of particulate trace metals (PTM) in both rivers, allows the production of highly realistic dissolved and particulate matter budgets which can further be broken down into their natural and anthropogenic counterparts (Dumas et al., 2015; Sadaoui et al., 2016).

Moreover, MOOSE has included standardized methods to quantify plankton (mainly zooplankton) and particles in its observation network at scales that match those of the physical variations. For example, trophic links between phytoplankton and zooplankton were studied in 2013 in a deep convection zone of the western Mediterranean Sea (Hunt et al., 2017). This study highlighted that in spring phytoplankton the average contributions to zooplankton biomass by pico-, nano-, and micro-phytoplankton were 42, 42, and 20%, respectively.

In parallel, several optical and imaging techniques are used to increase the spatial and temporal coverage of biological observation. These methods, while having less taxonomic resolution than microscopic counts, allow for a rapid determination of plankton and particle community size distributions [Underwater Video Profiler (UVP), Picheral et al., 2010]. In the Gulf of Lion, UVP data combined with net samples enabled the investigation of the impacts of deep-water convection on the biology of the gulf, suggesting an enhancement of energy transfer to higher trophic levels and organic matter export in the area (Donoso et al., 2017). Finally, consistent deployments of the UVP in the Mediterranean Sea, combined with drifting sediment trap data from over the last two decades, led to the first assessment of carbon export at the basin scale level (Ramondenc, 2017). All of the above examples show the great potential of coupling advance imaging and optical methods with more "traditional" techniques in order to better understand the tight coupling between physical and biological mechanisms in the Mediterranean Sea.

Discussion

Employing ILICO ambitions on another scale, the MOOSE network is creating a solid and transparent organization that can provide operational services for the timely, continuous, and sustainable delivery of high-quality environmental data and informational products related to the northwestern Mediterranean environment. Through MOOSE, the French Mediterranean community is now able to have a permanent monitoring system of ocean dynamics covering coastal and open ocean areas. MOOSE also provides a large flux of real-time data to facilitate validation of operational oceanographic models. With many years of research lying ahead for the MOOSE project, it is expected that the system will have an impact on marine science and policy in both the short- and long-term. In terms of marine observation, it is likely that the team's delivery of products, such as measurements and indicators of change and impact, will be widely used for policy decisions. These could potentially range from energy and pollution control, to fisheries quota determinations.

Like ILICO, the MOOSE project is not intended to develop sensors and new technologies, but the observation system must be ready to host sensors (according to the scientific needs) and to guide their development or integrate them when they are sustained.

For the next step, MOOSE, together with ILICO, will oversee the implementation of new parameters and platforms according to their readiness levels, allowing the timely implementation of components that are already mature, while encouraging innovation and formal efforts to improve readiness and build capacity. Moreover, it seems crucial to better structure the relationship between the coastal system, which is ideal to observe anthropogenic impact, and the open ocean system, a perfect area for climate change issues due to the space and timescales of the processes studied.

DISCUSSION AND RECOMMENDATIONS

Discussion

ILICO has a wealth of significant contributions from constituent networks in terms of implementation and standardized monitoring strategies, the development of new parameter collection techniques, new sensors and technology data use, inter-site collaboration, and a connection to wider communities and end-users.

Added Value of ILICO

Governing body-wise

Regrouping various fundamental observatory networks, ILICO made it possible to facilitate the individual organization and governing bodies of each. Some mandatory committees have been pooled between certain networks and ILICO, such as the international scientific council, which provides a global vision of the scientific interactions between the networks and the international community. Whereas financial and strategic discussions used to be conducted at individual levels, the inter-institution committee brings together the directorates of the organizations involved in ILICO to discuss the human and financial resources put in place by the various authorities (**Figure 8**, governance).

Scientific emulation-wise

Each of ILICO's research teams are responsible for the scientific valorization of their collected data. However, ILICO participates in the scientific outreach of the community via a network representative of the entire coastal ocean and nearshore scientific community. This scientific transverse outreach network can be seen as a forum: (i) for the scientific community involved with the observation networks, (ii) for prospective scientific reflection concerning the observation and understanding of the functioning of the nearshore and littoral environment, (iii) for cross-cutting questions to elementary networks, (iv) for expertise, reflection, and proposals on specific requests of ILICO or any related organizations, and (v) for reflection and possible structuring of new observation networks.

An example of a collective brainstorming event was the EVOLECO (ECOsystem EVOLution) symposium, whose objective was to draw up an inventory of the long-term evolution of coastal ecosystems (through the study of a 10-year time series from ILICO's elementary observatory) and to identify the associated forcings and processes. Two workshop needs emerged: (i) Comparison of the different statistical tools implemented on the long data series of the different networks, and (ii) the origin of the discrepancies observed between the 1990s and the 2000s on sets of parameters acquired by several networks.

In addition to defining scientific hot spots and super sites, the co-localization elementary networks acquisition also allows the sharing of:

- Scientific parameters: for example, the SONEL water levels could directly be used for coastline monitoring by DYNALIT.
- Measurement tools: for instance, the sea state monitoring camera makes it possible to monitor the evolution of some benthic habitats.

Data dissemination strategies-wise

The main objective of an observation service is to provide relevant, reliable, and qualified data on a studied scientific

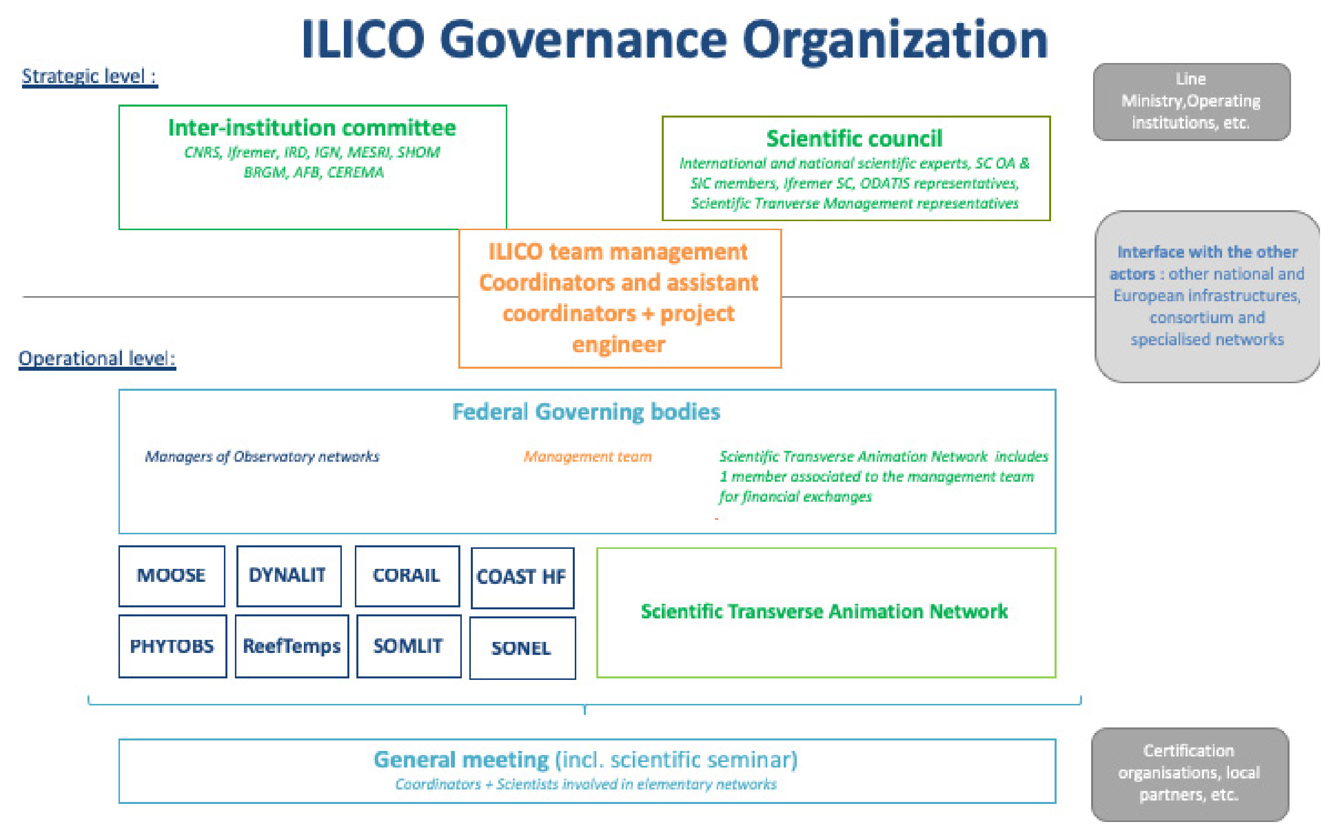

FIGURE 8 | ILICO governance organization.

phenomenon. Furthermore, data have to be shared with the wider scientific community and other end-users.

Early on, ILICO's observation networks developed individual or mutualized strategies and data infrastructures to quickly share and disseminate these observation measurements and products, with respect to the INSPIRE Directive from the European Commission (Directive 2007/2/CE of European Parliament and Council, March 14, 2007), and in the spirit of "open data" (Hocdé and Fiat, 2013). The data management of observation systems has significantly evolved in the last 10–15 years with the implementation of shared information systems, the adoption of standards, specifications, and guidelines, and the development of interoperable technologies and web services, etc. In a context where pre-existing networks had heterogenous developments in terms of interoperability, ILICO promotes the adoption and use of the best practices within FAIR guiding principles for scientific data management (Findable, Accessible, Interoperable, and Re-usable) (Wilkinson et al., 2016) and transfer of documentation into a Data Management Plan (DMP) with a shared and common metadata infrastructure, in collaboration with the national research data infrastructure SYSTEME TERRE and its specific interface dedicated to Ocean DATa Information and Services (ODATIS) to provide new services and products through a national portal in accordance with European standards.

Members of ILICO are also involved in several pan-European initiatives and numerical infrastructures (SeaDataNet and SeaDataCloud, EMODnet, Copernicus Marine Environment Monitoring Service, etc.) and other regional data web portals (AODN, IMOS, etc.). The intersection of all these data sources, combined with the expertise of ILICO scientists, will provide new added-value services and products.

Complementary Approaches of Spatial Coverage

ILICO elementary observatories were deployed following three major types of spatial strategies: the first type is a regional pattern that aims at revealing the spatial dynamics of the observed processes; the second type involves sampling a range of sites that are representative of different types of dynamics; the third type involves sampling a range of sites with different gradients of drivers and/or functioning.

(1) Studying spatial (as well as temporal) dynamics: This goal requires studying a spatial distribution adapted to spatial dynamics, while the sampling strategy must be homogeneous along the different sites. Within ILICO, the SONEL observatory for sea level, the MOOSE regional observatory of the Mediterranean coastal zone, the REEFTEMPS and CORAIL observation networks in the Pacific, and the PHYTOBS observatory for phytoplankton were conceived in this way. Within these networks, single-point observations generally have little value, but the intercomparing, or spatial combination, of observations at

different points brings more scientific value to the data. It allows for the building of a reference to which individual observations may be compared, to help distinguish local from global effects, to study spatial dynamics such as the propagation of a phenomenon, and to build regional diagnoses over the whole observed region.

(2) Studying independent, representative examples of sites: Within ILICO, the high-frequency automatic sampling platforms Coast-HF and the coastline dynamics observatory DYNALIT both follow this strategy: each observation site illuminates the functioning of local dynamics. The comparison of two different sites in the network makes sense only if these sites have comparable physiographic properties. The combination of all observation sites hardly draws a regional picture, and calculating an overall average, for instance, may not make sense. However, data from a sampled site may help understand the processes at work in a different site, not sampled, but with comparable physiographic conditions.

(3) Studying sample sites along gradients: Within ILICO, the SOMLIT observatory of water properties, some high-frequency automatic sampling platforms from COAST-HF, and some PHYTOBS sites are designed in such a way. Sampling sites and (eco)systems are selected within gradients of mechanisms like climate, tidal regimes, trophic regimes, geomorphology, turbidity, continental influence, etc. It allows a better identification and even quantification of the role of often interconnected mechanisms in the functioning and long-term change of (eco)systems.

These three types of spatial strategies are not fully exclusive: sampling sites typical of local dynamics may also be within the gradients of different mechanisms. Thus, selected sites can have local, regional, or large-scale interest, depending on the overall spatial sampling strategy. The challenge of ILICO is then to facilitate the articulation of scales from local to global.

An Ongoing Europeanization

Because ocean observations call for an integrative approach that overcomes national borders, ILICO has been designed to promote international collaborations, and more particularly a European structuration of coastal and nearshore observation efforts.

Thus, while the role of Member States remains central in developing and financing research infrastructures, the European Union plays an important part in supporting infrastructure, fostering the emergence of new facilities, opening up broad access to national and European infrastructures, and making sure that regional, national, European, and international policies are consistent and effective. It is not only necessary to avoid duplication of efforts and to coordinate and rationalize the use of the facilities, but also to pool resources so that the Union can also acquire and operate research infrastructures worldwide.

Ocean observation data life cycles can benefit from many European initiatives supported by the Directorate-General (DG) Mare (EMODnet), the DG Environment (Marine Strategy Framework Directive), the DG Grow (Copernicus Marine Services), and the DG Research and Innovation, mainly through Framework Programs (FP) for research and technological development.

The recent approach to research infrastructures by the European Framework Programs for research and technological development has made remarkable progress with the implementation of the European Strategy Forum on Research Infrastructures (ESFRI) roadmap that identifies vital new European Research Infrastructures for the next 10–20 years, integrates and opens national research facilities, and develops e-infrastructures underpinning a digital European Research Area. The networks of research infrastructures across Europe strengthen its human capital base by providing world-class training for a new generation of researchers and engineers and promoting interdisciplinary collaboration.

As far as marine sciences are concerned, the FP/Infrastructure involves support Research Infrastructures such as research vessels (Euro fleets projects), the Argo floats program (Euro ARGO), the European Marine Seas Observatory (EMSO), and the European Marine Biological Resource Centre (EMBRC).

In the field of coastal observation, the European Union has financed two projects: JERICO – Joint European Research Infrastructure for Coastal Observation (FP7 project under grant agreement No. n° 262584 Project coordinator: Ifremer, France – 2007–2013) and JERICO-NEXT (H2020 project under grant agreement No. 654410 Project coordinator: Ifremer, France – 2015–2019, Farcy et al., in preparation). A part of ILICO lies within the thematic scope of JERICO and JERICO-NEXT. The next step is to propose a permanent, sustained, European Observation Infrastructure for the coastal and nearshore marine environment, to be included in the ESFRI Roadmap and with respect to the emerging European Ocean Observing System, EOOS, an inclusive voluntary federation of diverse ocean observation and monitoring communities. Accredited by the French ministry for higher education and research, the ILICO infrastructure would be, entirely or in part, a component of this European infrastructure.

The aim of this European Infrastructure would be to provide one integrated system that can deliver information on coastal and shelf seas across three key application areas: marine ecosystem health, operational services, and climate. It is based on multi-platform and integrated approaches, in the continuity of the JERICO and JERICO-NEXT projects, and will be driven by science and societal needs and impacts. The European Infrastructure will also aim at filling the two following current "gaps": (1) interface with the open ocean and (2) the land–sea continuum, and lead the coastal ocean observing community in growing an integrated, responsive, and sustained European observing system.

Recommendation – Coastal Ocean and Nearshore Observation 10 Years From Now

Scientifically Oriented Observation Strategies

When designing a long-term observation system, one may wonder how the research questions will evolve over the next decade. When developing ILICO's strategy based on long-term parameter observations, we expect most of these questions still to be relevant 10 years from now. However, depending on the evolution of global change, new questions about systems resilience and adaptation could be addressed and new communities and end-users could be interested in ILICO data. In the coming years, ILICO will develop adaptation skills and foster cross-disciplinary research and *trans*-existing network interactions (for example, the understanding of long-term physical evolution of the morphological aspects of the coast in relation with the evolution of sea level.) in order to increase its robustness.

Technical and Methodological Issues/Innovation Trends

In the coming years, progress regarding observation strategies will emerge from:

Auto-adaptive abilities

In the next decades temporal and spatial resolutions of data acquisition will certainly address the issue of fitting the high spatial and temporal scales of the processes involved in coastal dynamics. Future sensors and platforms will enable one to auto-adapt temporal and spatial sampling depending on external parameters, with the aim, for example, of acquiring data during extreme/rare metrological events.

The use of archival data and data-mining will be extended. For example, currently the estimation of the change in global sea level rise over the last century strongly depends on a small set of very long-term sea-level time series. It is important to take advantage of the mass of information that was collected in the past and which lies dormant in a number of French archives.

A sober use of resources (including human resources)

Constraint being a great source of innovation, one can expect that raising environmental concerns will generate a new generation of sensors and methods more sustainable and creating less damage to nature.

Furthermore, as previously described, most of the elementary observatories require high human-resources. Some new techniques will have to be developed in order to optimize staff hours and costs, so that financial support could guarantee all human skills and expertise when necessary.

Strong connections (to real-time communications access, to other scientific communities, to end-users)

Real-time acquisition could be of great interest in order to limit the step of data recovery. Furthermore, in the perspective of making the observatories more up front and modeled as an 'alert system' rather than the present registering systems, the coastal ocean and nearshore observation system must develop a real-time data connection. The real time survey will make these systems act more as an alert network that will inform of any ongoing change and notify scientists and stakeholders earlier so they may make rapid decisions regarding specific monitoring and early conservation. This will require strong interoperability and standardization of systems and will also raise some issues about data validation and ownership.

Finally, possible future trajectories of ecosystems have to be identified for sustainable ecosystem management. For that, predictive models are needed. Long-term data sets are precious data sets for building and testing such models. Thus, a close relationship between long-term data providers and predictive modelers should be encouraged, as well as co-construction with end-users in order to maximize their impacts.

How Coastal Ocean and Nearshore Observation Can Contribute to a Better Management of Coastal Zones

While ILICO's infrastructure is a science-based initiative motivated by academic research and purposes, it seems increasingly likely that, in the coming years, ILICO will tend to develop more operational services dedicated to the better management of coastal zones.

Coastal science fosters the resilience of coastal communities by anticipating hazards to human and ecosystem health, safety, and welfare. Accelerating coastal changes advocate for the increased accuracy and precision of predictions of future conditions at global, regional, and local spatial scales and on decadal, annual, and event time scales. The ILICO research collaborations crossing the broadest range of disciplines and coastal landscapes are ideally positioned to help meet these future challenges.

For the next decade, with ILICO becoming fully integrated and operational, observations should be able to guide policy decisions and reduce the risks to coastal communities from natural hazards and climate change, notably by:

- Giving an accurate picture of the coastal ocean state for stakeholders – can help for coastal management (for example: periods of harmful algal blooms, hydrodynamical conditions for future public/private infrastructure projects, evaluation of potential – renewable – energy).
- Contributing to the management and adaptation strategies of extreme events.
- Enhancing observational data assessment and integration to models in order to deliver long-term trend management and forecast.

CONCLUSION

ILICO, the French initiative for adding value to scattered existing institutional coastal ocean and nearshore observatories and observation initiatives, is an innovative, adaptable, and inclusive infrastructure. Such an organization enables efficient multi-instrument monitoring (through mutualization of instruments and best practices) and fit-for-purpose developments connected to scientific communities.

In the context of increasing and pressing needs for ocean information (for example: United Nations Sustainable Development Goal 14), ILICO, as a science driven infrastructure, has a growing role to play in underpinning nearshore economic activities, while ensuring the protection of coastal environments.

This could be achieved by contributing to:

- Understand environmental and economic pressures on our coasts.
- Produce and deliver nearshore and coastal information to support blue growth and sustainable development.
- Raise societal awareness so as to become a public utility by 2030.

Over the next decades, ILICO will keep promoting better coordinated and sustained coastal ocean observing, and the study of ocean variables relevant to society and the global ecosystem. To do so, a fruitful gap analysis could address missing observations, missing data, sustainability gaps as well as technology gaps, but first and foremost, European and international collaborations need to be built.

AUTHOR CONTRIBUTIONS

LuC, CD, JP, and PhR contributed to the conception or design of the infrastructure. LuC, CD, and JP wrote the first draft of the manuscript. JA, BC, GC, JC, PC, LaC, RH, SP, PaR, NS, LT, and RV wrote sections of the manuscript.

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REFERENCES

Alory, G., Vega, A., Ganachaud, A., and Despinoy, M. (2006). Influence of upwelling, subsurface stratification, and heat fluxes on coastal sea surface temperature off southwestern New Caledonia. *J. Geophys. Res.* 111, 1–9. doi: 10.1029/2005JC003401.

Autret, R., Dodet, G., Fichaut, B., Suanez, S., David, L., Leckler, F., et al. (2016). A comprehensive hydro-geomorphic study of cliff-top storm deposits on Banneg Island during winter 2013–2014. *Mar. Geol.* 382, 37–55. doi: 10.1016/j.margeo.2016.09.014

Baschek, B., Schroeder, F., Brix, H., Riethmüller, R., Badewien, T. H., Breitbach, G., et al. (2017). The coastal observing system for northern and arctic seas (COSYNA). *Ocean Sci.* 13, 379–410. doi: 10.5194/os-13-379-2017

Béthoux, J.-P., Morin, P., and Ruiz-Pino, D. (2002). Temporal trends in nutrient ratios: chemical evidence of mediterranean ecosystem changes driven by human activity. *Deep Sea Res. Part II Top. Stud. Oceanogr.* 49, 2007–2016. doi: 10.1016/S0967-0645(02)00024-3

Béthoux, J.-P., and Tailliez, D. (1994). "Deep-Water in the Western Mediterranean Sea, Yearly Climatic Signature and Enigmatic Spreading," in *Ocean Processes in Climate Dynamics: Global and Mediterranean Examples. NATO ASI Series (Series C: Mathematical and Physical Sciences)*, eds P. Malanotte-Rizzoli and A. R. Robinson (Berlin: Springer).

Blain, S., Guillou, J., Treguer, P., Woerther, P., Delauney, L., Follenfant, E., et al. (2004). High frequency monitoring of the coastal marine environment using the MAREL buoy. *J. Environ Monitor.* 6, 569–575. doi: 10.1039/b314073c

Bosse, A., Testor, P., Houpert, L., Damien, P., Prieur, L., Hayes, D., et al. (2016). Scales and dynamics of submesoscale coherent vortices formed by deep convection in the northwestern mediterranean sea. *J. Geophys. Res. Oceans* 121, 7716–7742. doi: 10.1002/2016jc012144

Bosse, A., Testor, P., Mortier, L., Prieur, L., Taillandier, V., D'Ortenzio, F., et al. (2015). Spreading of levantine intermediate waters by submesoscale coherent vortices in the northwestern mediterranean sea as observed with gliders. *J. Geophys. Res. Oceans* 120, 1599–1622. doi: 10.1002/2014jc010263

Burvingt, O., Masselink, G., Scott, T., Davidson, M., and Russell, P. (2018). Climate forcing of regionally-coherent extreme storm impact and recovery on embayed beaches. *Mar. Geol.* 401, 112–128. doi: 10.1016/j.margeo.2018.04.004

Castelle, B., Dodet, G., Masselink, G., and Scott, T. (2017). A new climate index controlling winter wave activity along the Atlantic coast of Europe: the West Europe pressure anomaly. *Geophys. Res. Lett.* 44, 1384–1392. doi: 10.1002/2016GL072379

Castelle, B., Dodet, G., Masselink, G., and Scott, T. (2018). Increased winter-mean wave height, variability, and periodicity in the Northeast Atlantic over 1949–2017. *Geophys. Res. Lett.* 45, 3586–3596. doi: 10.1002/2017GL076884

Castelle, B., Marieu, V., Bujan, S., Splinter, K. D., Robinet, A., Sénéchal, N., et al. (2015). Impact of the winter 2013–2014 series of severe Western Europe storms on a double-barred sandy coast: beach and dune erosion and megacusp embayments. *Geomorphology* 238, 135–148. doi: 10.1016/j.geomorph.2015.03.006

Coppola, L., Legendre, L., Lefevre, D., Prieur, L., Taillandier, V., and Diamond Riquier, E. (2018). Seasonal and inter-annual variations of dissolved oxygen in the northwestern mediterranean Sea (DYFAMED site). *Prog. Oceanogr.* 162, 187–201. doi: 10.1016/j.pocean.2018.03.001

Damien, P., Bosse, A., Testor, P., Marsaleix, P., and Estournel, C. (2017). Modeling Postconvective submesoscale coherent vortices in the Northwestern Mediterranean Sea. *J. Geophys. Res. Oceans* 122, 9937–9961. doi: 10.1002/2016jc012114

Davies, H. C. (2015). Weather chains during the 2013/2014 winter and their significance for seasonal prediction. *Nat. Geosci.* 8, 833–837. doi: 10.1038/ngeo2561

Davis, R. A., and Ethington, R. L. (1976). Beach and nearshore sedimentation. *SEPM Soc. Sediment. Geol.* 24. doi: 10.2110/pec.76.24

Dodet, G., Castelle, B., Masselink, G., Scott, T., Davidson, M., Floc'h, F., et al. (2019). Beach recovery from extreme storm activity during the 2013–14 winter along the Atlantic coast of Europe. *Earth Surf. Process. Landf.* 44, 393–401. doi: 10.1002/esp.4500

Donoso, K., Carlotti, F., Pagano, M., Hunt, B. P. V., Escribano, R., and Berline, L. (2017). Zooplanktoncommunity response to the winter2013 deep convection process in the NW Mediterranean Sea. *J. Geophys. Res. Oceans* 122, 2319–2338. doi: 10.1002/2016JC012176

Dumas, C., Ludwig, W., Aubert, D., Eyrolle, F., Raimbault, P., Gueneugues, A., et al. (2015). Riverine transfer of anthropogenic and natural trace metals to the Gulf of Lions (NW Mediterranean Sea). *Appl. Geochem.* 58, 14–25. doi: 10.1016/j.apgeochem.2015.02.017

Durrieu de Madron, X., Houpert, L., Puig, P., Sanchez-Vidal, A., Testor, P., Bosse, A., et al. (2013). Interaction of dense shelf water cascading and open-sea convection in the northwestern Mediterranean during winter 2012. *Geophys. Res. Lett.* 40, 1379–1385. doi: 10.1002/grl.50331

Galzin, R., Lecchini, D., Lison de Loma, T., Moritz, C., Parravicini, V., and Siu, G. (2015). Long term monitoring of coral and fish assemblages (1983-2014) in Tiahura reefs, Moorea, French Polynesia. *Cybium* 40, 031–041.

Goberville, E., Beaugrand, G., Sautour, B., Tréguer, P., and Team, S. (2010). Climate-driven changes in coastal marine systems of western Europe. *Mar. Ecol. Prog. Ser.* 408, 129–148. doi: 10.3354/meps08564

Hernández-Fariñas, T., Soudant, D., Barille, L., Belin, C., Lefebvre, A., Bacher, C., et al. (2014). Temporal changes in the phytoplankton community along the french coast of the eastern english channel and the southern bight of the North Sea. *ICES J. Mar. Sci.* 71, 821–833. doi: 10.1093/icesjms/fst192

Hocdé, R., and Fiat, S. (2013). Le système d'information du "réseau de capteurs de température des eaux côtières dans la région du Pacifique Sud et Sud-Ouest?". *Netcom* 27, 170–173. doi: 10.4000/netcom.1294

Houpert, L., Testor, P., Durrieu de Madron, X., Somot, S., D'Ortenzio, F., Estournel, C., et al. (2015). Seasonal cycle of the mixed layer, the seasonal thermocline and the upper-ocean heat storage rate in the mediterranean Sea derived from observations. *Prog. Oceanogr.* 132, 333–352. doi: 10.1016/j.pocean.2014.11.004

Hunt, B. P. V., Carlotti, F., Donoso, K., Pagano, M., D'Ortenzio, F., Taillandier, V., et al. (2017). Trophic pathways of phytoplankton size classes through the

zooplankton food web over the spring transition period in the north-west Mediterranean Sea. *J. Geophys. Res. Oceans* 122, 6309–6324. doi: 10.1002/2016jc012658
Krahmann, G., and Schott, F. (1998). Longterm increases in Western Mediterranean salinities and temperatures: anthropogenic and climatic sources. *Geophys. Res. Lett.* 22, 4209–4212. doi: 10.1029/1998gl900143
Lamy, T., Galzin, R., Kulbicki, M., Lison de Loma, T., and Claudet, J. (2016). Three decades of recurrent declines and recoveries in corals belie ongoing change in fish assemblages. *Coral Reefs* 35, 293–302. doi: 10.1007/s00338-015-1371-2
Lemos, C., Floc'h, F., Yates, M., Le Dantec, N., Marieu, V., Hamon, K., et al. (2018). Equilibrium modeling of the beach profile on a macrotidal embayed low tide terrace beach. *Ocean Dyn.* 68, 1207–1220. doi: 10.1007/s10236-018-1185-1
Liénart, C., Savoye, N., Bozec, Y., Breton, E., Conan, P., David, V., et al. (2017). Dynamics of particulate organic matter composition in coastal systems: a spatio-temporal study at multi-systems scale. *Prog. Oceanogr.* 156, 221–239. doi: 10.1016/j.pocean.2017.03.001
Liénart, C., Savoye, N., David, V., Ramond, P., Rodriguez Tress, P., Hanquiez, V., et al. (2018). Dynamics of particulate organic matter composition in coastal systems: forcing of spatio-temporal variability at multi-systems scale. *Prog. Oceanogr.* 162, 271–289. doi: 10.1016/j.pocean.2018.02.026
Lorenzoni, L., and Benway, H. M. (2013). *Global Intercomparability in a Changing Ocean: an International Time-Series Methods Workshop*. Bermuda: Bermuda Institute of Ocean Sciences.
Many, G., Bourrin, F., Durrieu de Madron, X., Pairaud, I., Gangloff, A., Doxaran, D., et al. (2016). Particle assemblage characterization in the rhone River ROFI. *J. Mar. Syst.* 157, 39–51. doi: 10.1016/j.jmarsys.2015.12.010
Marchesiello, P., Lefèvre, J., Vega, A., Couvelard, X., and Menkes, C. (2010). Coastal upwelling, circulation and heat balance around New Caledonia's barrier reef. *Mar. Pollut. Bull.* 61, 432–448. doi: 10.1016/j.marpolbul.2010.06.043
Masselink, G., Castelle, B., Scott, T., Dodet, G., Suanez, S., Jackson, D., et al. (2016). Extreme wave activity during 2013/2014 winter and morphological impacts along the Atlantic coast of Europe. *Geophys. Res. Lett.* 43, 2135–2143. doi: 10.1002/2015GL067492
Masselink, G., Scott, T., Poate, T., Russell, P., Davidson, M., and Conley, D. (2015). The extreme 2013/2014 winter storms: hydrodynamic forcing and coastal response along the southwest coast of England. *Earth Sur. Process. Landf.* 41, 378–391. doi: 10.1002/esp.3836
Ouillon, S., Douillet, P., Fichez, R., and Panché, J.-Y. (2005). Enhancement of regional variations in salinity and temperature in a coral reef lagoon, New Caledonia. *Comptes Rendus Geosci.* 337, 1393–1582.
Petihakis, G., Perivoliotis, L., Korres, G., Ballas, D., Frangoulis, C., Pagonis, P., et al. (2018). An integrated open-coastal biogeochemistry, ecosystem and biodiversity observatory of the eastern mediterranean – the cretan sea component of the POSEIDON system. *Ocean Sci.* 14, 1223–1245. doi: 10.5194/os-14-1223-2018
Picheral, M., Guidi, L., Stemmann, L., Karl, D. M., Iddaoud, G., Gorsky, G., et al. (2010). The underwater vision profiler 5: an advanced instrument for high spatial resolution studies of particle size spectra and zooplankton. *Limnol. Oceanogr.. Methods* 8, 462–473. doi: 10.4319/lom.2010.8.462
Pouvreau, N. (2008). *Trois Cents ans de Mesures Marégraphiques en France: Outils, Méthodes et Tendances des Composantes du Niveau de la Mer au Port de Brest*. Available at: https://tel.archives-ouvertes.fr/tel-00353660/document. (accessed September 26, 2008).
Ramondenc, S. (2017). *Analyse Des Variations Spatio-Temporelles Du Zooplancton Gélatineux et Son Effet Sur Les Flux De Matières à l'aide d'une Approche Combinant Expérimentation et Écologie Numérique*. Paris: Ecologie, Environnement. Université Pierre et Marie Curie.
Rixen, M., Beckers, J. M., Levitus, S., Antonov, J. T., Boyer, T. C., Maillard, C., et al. (2005). The western mediterranean deep water: a proxy for climate change. *Geophys. Res. Lett.* 32:L12608. doi: 10.1029/2005GL022702
Robinet, A., Idier, D., Castelle, B., and Marieu, V. (2018). A reduced-complexity shoreline change model combining longshore and cross-shore processes: the lx-shore model. *Environ. Model. Soft.* 109, 1–16. doi: 10.1016/j.envsoft.2018.08.010
Rohling, E. J., and Bryden, H. L. (1992). Man-induced salinity and temperature increases in western mediterranean deep water. *J. Geophys. Res.* 97, 11191–11198. doi: 10.1038/srep23009
Rombouts, I., Simon, N., Aubert, A., Cariou, T., Feunteun, E., Guérin, L., et al. (2019). Changes in marine phytoplankton diversity: assessment under the marine strategy framework directive. *Ecol. Indic.* 102, 265–277. doi: 10.1016/j.ecolind.2019.02.009
Sadaoui, M., Ludwig, W., Bourrin, B., and Raimbault, P. (2016). Controls, budgets and variability of riverine sediment fluxes to the Gulf of lions (NW Mediterranean Sea). *J. Hydrol.* 540, 1002–1015. doi: 10.1016/j.jhydrol.2016.07.012
Send, U., Font, J., Krahmann, G., Millot, C., Rhein, M., and Tintoré, J. (1999). Recent advances in observing the physical oceanography of the western Mediterranean Sea. *Prog. Oceanogr.* 44, 37–64. doi: 10.1016/S0079-6611(99)00020-8
Somot, S., Houpert, L., Sevault, F., Testor, P., Bosse, A., Taupier-Letage, I., et al. (2016). Characterizing, modelling and understanding the climate variability of the deep water formation in the North-Western Mediterranean Sea. *Clim. Dyn.* 51, 1179–1210. doi: 10.1007/s00382-016-3295-0
Splinter, K. D., Turner, I. L., Davidson, M. A., Barnard, P., Castelle, B., and Oltman-Shay, J. (2014). A generalizedequilibrium model for predicting dailyto interannual shoreline response. *J. Geophys. Res. Earth Surf.* 119, 1936–1958. doi: 10.1002/2014jf003106
Talarmin, A., Lomas, M. W., Bozec, Y., Savoye, N., Frigstad, H., Karl, D. M., et al. (2016). Seasonal and long-term changes in elemental concentrations and ratios of marine particulate organic matter. *Global Biogeochem. Cycles* 30, 1699–1711. doi: 10.1002/2016GB005409
Testut, L., Wöppelmann, G., Simon, B., and Téchiné, P. (2006). The sea level at Port-aux-Français, Kerguelen Island, from 1949 to the present. *Ocean Dyn.* 56, 464–472. doi: 10.1007/s10236-005-0056-8
Thorel, M., Claquin, P., Schapira, M., Le Gendre, R., Riou, P., Goux, D., et al. (2017). Nutrient ratios influence variability in pseudo-nitzschia species diversity and particulate domoic acid production in the Bay of Seine (France). *Harmful Algae* 68, 192–205. doi: 10.1016/j.hal.2017.07.005
Vitousek, S., Barnard, P. L., Limber, P., Erikson, L., and Cole, B. (2017). A model integrating longshore and cross-shore processes for predicting long-term shoreline response to climate change. *J. Geophys. Res. Earth Surf.* 122, 782–806. doi: 10.1002/2016JF004065
Widdicombe, C. E., Eloire, D., Harbour, D., Harris, R. P., and Somerfield, P. J. (2010). Long-term phytoplankton community dynamics in the Western English Channel. *J. Plankton Res.* 32, 643–655. doi: 10.1016/j.marenvres.2017.04.013
Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., Appleton, G., Axton, M., Baak, A., et al. (2016). The FAIR guiding principles for scientific data management and stewardship. *Sci. Data* 3:160018
Wiltshire, K. H., Kraberg, A., Bartsch, I., Boersma, M., Franke, H.-D., Freund, J., et al. (2010). Helgoland Roads, North Sea: 45 Years of Change. *Estuaries Coast.* 33, 295–310. doi: 10.1007/s12237-009-9228-y
Woppelmann, G., Pouvreau, N., and Simon, B. (2006). Brest sea level record: a time series construction back to the early eighteenth century. *Ocean Dyn.* 56, 487–497. doi: 10.1007/s10236-005-0044-z
Yates, M., Guza, R., O'Reilly, W. C., and Seymour, R. J. (2009). Overview of seasonal sand level changes on Southern California beaches. *Shore Beach.* 77, 1–46.
Zappa, G., Shaffrey, L. C., Hodges, K. I., Sansom, P. G., and Stephenson, D. B. (2013). A Multimodel assessment of future projections of north atlantic and european extratropical cyclones in the cmip5 climate models. *J. Clim.* 26, 5846–5862. doi: 10.1175/jcli-d-12-00573.1

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Ocean Observations Required to Minimize Uncertainty in Global Tsunami Forecasts, Warnings, and Emergency Response

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It is possible that no catastrophe has mobilized the global ocean science and coastal emergency management communities more than the 2004 Indian Ocean tsunami. Though the Pacific tsunami threat was recognized, and a warning system had been in place since 1965, there was no warning system in the Indian Ocean, and almost 230,000 people perished. More broadly, the event highlighted critical gaps in global tsunami science and observation systems. In 2004, real-time coastal and deep-ocean observation systems were almost non-existent. Tsunami sources were inferred based on rough seismic parameters. Since then, tremendous strides have been made under the auspices of IOC/UNESCO toward better understanding tsunami mechanisms, deploying advanced real-time tsunami observation systems, and establishing tsunami warning and mitigation systems for the four main ocean basins at risk from tsunamis. Nevertheless, significant detection, measurement, and forecast uncertainties remain to meet emergency response and community needs. A new generation of ocean sensing capabilities presents an opportunity to address several of these uncertainties. Ocean bottom pressures can be measured over dense, multisensor grids linking stand-alone buoy systems with emerging capabilities like fiber-optic cables. The increasing number of coastal sea-level stations provides the higher time and space resolution needed to better verify forecasts and account for local variability. In addition, GNSS sensors may be able to provide solid-earth data needed to define seismic tsunami sources more precisely in the short timescales required. When combined with advances in seismology, other emerging techniques, and state-of-the-art modeling and computational resources, these capabilities will enable more timely and accurate tsunami detection, measurement, and forecasts. Because of these advances in detection and measurement, the opportunity exists to greatly reduce and/or quantify uncertainties associated with forecasting tsunamis. Providing more timely and accurate information related to tsunami location, arrival time, height, inundation, and duration would improve public trust and confidence and fundamentally alter tsunami emergency response. Additionally, this capability could be integrated with related fields (e.g., storm surge, sea-level rise, tide predictions, and ocean forecasting) to develop and deploy one continuous, real-time, accurate depiction of the always moving boundary that separates ocean from coast and, sometimes, life from death.

Keywords: tsunami, detection, forecast, warning, mitigation, near field, uncertainty

INTRODUCTION

To emergency managers charged with protecting populations from weather-related hazards, uncertainty is a formidable challenge. Numerical weather prediction models require detailed initialization data, and associated instrumentation, over massive domains to produce accurate forecasts. Plus, no matter how well these models represent initial conditions, uncertainties inevitably grow over the period of a model run. Resulting errors create public doubt and can lead to inconsistent responses no matter how much urgency emergency managers convey.

Similar challenges exist in the tsunami community, though the uncertainties manifest differently. Tsunamis propagate and amplify at reliable rates in the deep ocean based on depth. Assuming all other variables are known, tsunami wave heights at any time and location in the open ocean can be reliably traced back to the wave conditions at the source.[1] Accurately defining these conditions, the source parameters, is therefore of utmost importance.

We recognize there are other sources of forecast errors unrelated to the tsunami source that must be considered. The complex modification of tsunami behavior when it reaches shallow water due to non-linear interactions and the often sparse coverage of high-resolution bathymetric data can lead to significant differences in forecast versus observed coastal wave heights. Reducing these errors will require dedicated, multiscale coastal mapping efforts, higher density of coastal observation systems, and increased sophistication of numerical simulations. The primary focus of this paper, however, is to comprehensively address one of the major limitations to accurate tsunami forecasts: the inability to quickly measure and represent the tsunami source.

Although principles of tsunami generation and propagation have long been understood, before the 2004 Indian Ocean tsunami, little real-time information was available regarding tsunami size and character, even for large ocean-wide tsunamis (Bernard et al., 2010). This was because there was no comprehensive global tsunami detection and measurement capability. There was no way to directly observe tsunamis until they reached coastal sea-level stations. Even then, data were typically not available in real time. It often took a day or more to accurately reconstruct critical tsunami source parameters using retrospective seismic analysis and sea-level observations (see orange line, **Figure 1**).

Fortunately, great strides have been made to reduce forecast uncertainties for tsunamis generated more than 3 h tsunami travel time away (distant-source or far-field tsunamis) (Bernard and Titov, 2015). Since the 2004 Indian Ocean tsunami, global tsunami detection, forecast, and warning capabilities have significantly expanded due to increased governmental support and international collaboration and data sharing. Greater availability of real-time seismic data and enhanced seismic analysis now enable estimation of earthquake forcing mechanisms within 2–3 h, and sometimes much sooner (see green line, **Figure 1**). Approximately 60 deep-ocean observation buoy systems and hundreds of tsunami-capable coastal sea-level stations ensure most large tsunamis will be detected and measured with sufficient time to alert distant coastlines.

Once measured in the deep ocean, tsunami arrival time, height, and duration at the coast can be accurately forecast using shallow-water wave equations (Thomson et al., 2011; Rabinovich et al., 2013). Given sufficient bathymetric data and computational resources, inundation can also be reliably calculated at the coast by nested-grid non-linear modeling (Hébert et al., 2001). Notably, lack of high-resolution bathymetric data is a problem for many ocean forecasting applications, including, tsunami warning.

Despite recent improvements to sensing and analysis capabilities, there are still large forecast uncertainties in the near field, where local-source tsunamis occur. Such tsunamis are particularly dangerous because they may reach a coast in less than 1 h, often less than 30 min, after generation. In extreme cases, they may strike in as little as 5–10 min.

[1]Tsunamis can be described mathematically as solutions to hyperbolic partial differential equations. This is a unique characteristic of hyperbolic systems and stands in contrast to other geophysical processes defined by parabolic or elliptic equations.

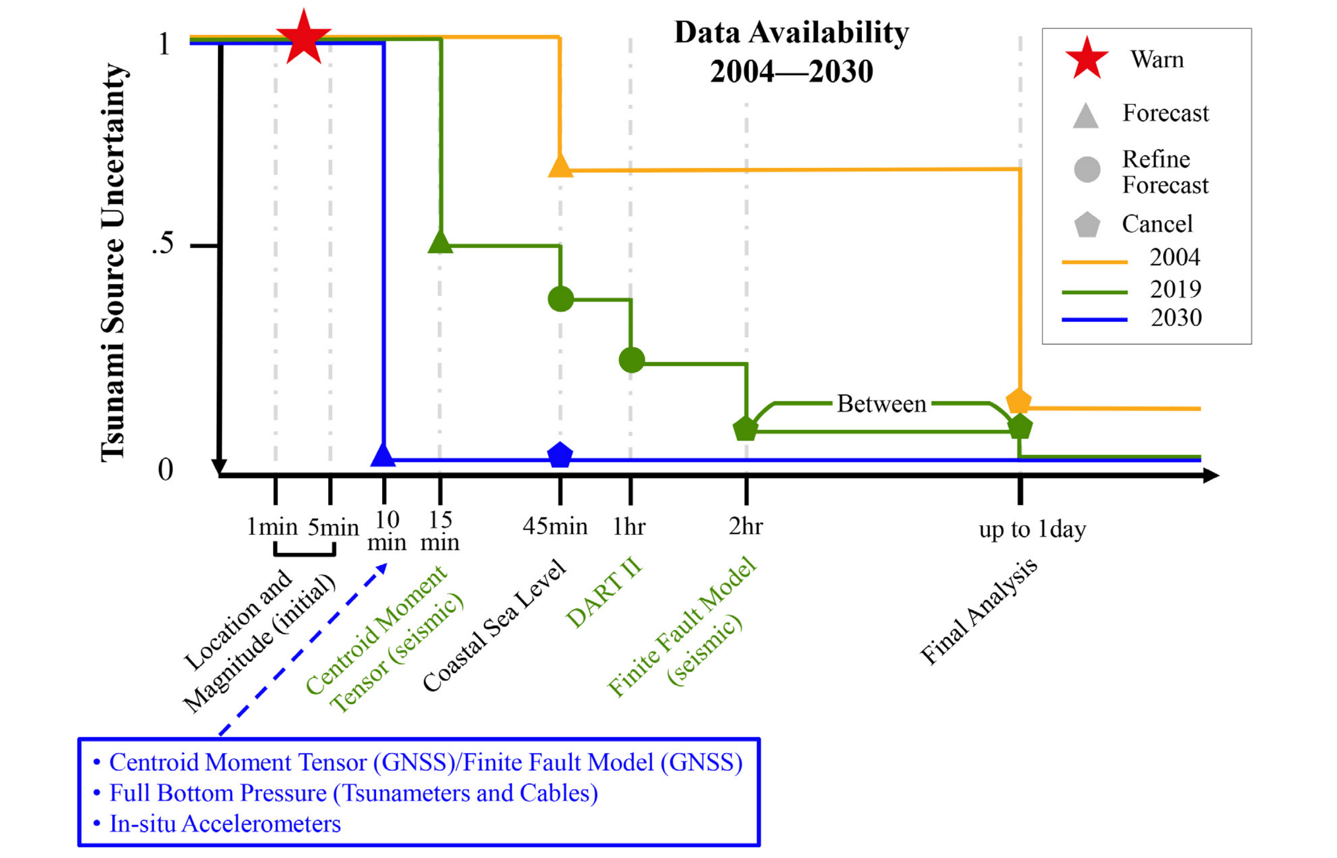

FIGURE 1 | Generalized relationship between tsunami source uncertainty and time after earthquake origin for three different time frames. The orange line represents tsunami source uncertainty levels prior to 2004, the green line represents tsunami source uncertainty levels at present (2019), and the blue line represents tsunami source uncertainty levels achievable with the ocean sensing and analysis techniques advocated for in this paper. Initial earthquake location and magnitude is considered "fully uncertain" in terms of solving tsunami source parameters for the purposes of this depiction.

Since it presently takes hours to precisely determine an earthquake's forcing mechanism, and observations are limited, emergency managers, particularly in the near field, face large impact uncertainties when deciding how to protect their communities. They must develop and execute preplanned protocols based on broad—sometimes false—assumptions about a tsunami's potential height and inundation. This can lead to over or under warning, the latter being particularly dangerous.

Fortunately, methods to more precisely and quickly measure tsunami sources are emerging. This will allow for development and delivery of accurate forecasts in time for emergency managers to take decisive action (Williamson and Newman, 2018). However, realizing this vision will require a reimagining and realignment of techniques, procedures, and observation networks.

Rapid seismic analysis is critical for issuing initial alerts, and efforts to refine and accelerate these techniques remain crucial. To directly infer tsunami sources in real time, however, more than traditional seismic analysis is needed.

This includes augmenting traditional seismic analysis with emerging capabilities, like using ground displacement data from the ever-expanding Global Navigation Satellite System (GNSS). We expect this to lead to more reliable tsunami source estimates where geography and/or instrument density support it.

In locations not supported by land-based GNSS-derived estimates, some countries are deploying advanced bottom pressure recorders (BPRs) on stand-alone deep-ocean buoy systems and, in Japan, Canada, and the United States, on limited-area cabled observation systems (Thomson et al., 2011; Rabinovich and Eblé, 2015). These instruments filter out seismic noise, allowing their placement much closer to likely seismic sources in the deep ocean, thereby reducing the time to measure the first wave from over an hour to tens of minutes.

This deep-ocean sensing strategy must be supported by high-density coastal observational data (Intergovernmental Oceanographic Commission [IOC], 2006, 2009, 2016). An expanded array of tsunami-capable coastal sea-level stations would help constrain tsunami sources and provide verification of real-time coastal wave height and inundation forecasts.

Most of these capabilities are currently available to the global tsunami warning and mitigation system or will be soon. When fully implemented, we expect a significant drop in tsunami source uncertainty, which will allow production of a dynamically based tsunami forecast within 10–15 min of tsunami generation (provided it is generated within a known source area).

As promising as these capabilities are, to more accurately measure and characterize all tsunami sources, we must look beyond them. Land-based GNSS and seismic processing techniques cannot directly measure seafloor deformation in most cases. This requires an *in situ* submarine network of localized, real-time displacement sensors deployed directly over a source.

Government and commercial entities regularly deploy submarine fiber-optic cables that could be important contributors to real-time tsunami detection and measurement. These cables cover key portions of nearly every tsunamigenic submarine zone in the world. Instrumenting these cables with real-time BPRs would greatly enhance the ability to verify wave propagation data and assimilate them into forecast models (Howe et al., 2018).

Direct instrumentation of fiber-optic cables requires commitments and resources beyond what regional tsunami warning and mitigation systems could provide on their own. Still, we can imagine a dynamic network of ocean observing systems (e.g., instrumented fiber-optic cables augmented by advanced stand-alone deep-ocean buoy systems) that could greatly reduce tsunami source uncertainty within minutes of generation, regardless of source location. If realized, the global tsunami warning and mitigation system would be able to deliver meaningful and accurate hydrodynamic tsunami forecasts within 10 min of generation (see blue line, **Figure 1**).

Other emerging techniques may also support the tsunami warning process. Satellite altimetry, infrasound arrays, and coastal high-frequency radar can provide important information (e.g., Barrick, 1979). A tsunami's distinct signature can even be detected in the ionosphere.

We are careful not to oversimplify the threat or overpromise the timeliness and accuracy that tsunami warning centers can deliver. There will always be locations too close to a tsunami source to consider anything other than full evacuation once a potentially tsunamigenic earthquake is detected. But for most tsunami-vulnerable coastlines, being able to accurately determine tsunami source parameters, in the targeted time frame, would drastically change how emergency managers coordinate and execute their responses.

Emergency managers would no longer need to consider multiple scenarios to account for uncertainties. More importantly, the public could respond more quickly and appropriately based on improved trust and confidence in the alerts. Ultimately, these changes could save lives.

Nevertheless, significant obstacles remain. For instance, few countries can afford to develop and deploy dedicated tsunami observation systems. Traditionally, fielded ocean observing systems are operated by commercial enterprises and academic organizations for non-tsunami-specific purposes. There are likely limited incentives for them to add such instrumentation to their systems much less operationally support it. Even if a global observational grid of sufficient density to fully constrain tsunami sources in real time was achieved, the need to condition the public to act quickly and appropriately based on the enhanced products would remain.

Despite these challenges, there has never been a greater opportunity to pursue sweeping tsunami forecast improvements, especially in the near field. This paper describes how the global tsunami warning and mitigation system could achieve such improvements.

BENEFITS OF REDUCING TSUNAMI FORECAST UNCERTAINTY

Reducing tsunami forecast uncertainty supports all aspects of emergency management. Ultimately, it will provide assurance to at-risk communities and help them with their decision-making and community response.

In the context of tsunami emergency and risk management, timely response is critical to saving lives and preventing loss. Political leaders and the public expect timely, accurate, and effective tsunami alerts. However, these expectations cannot currently be fully met. While considerable improvements to tsunami warning and mitigation systems have saved many lives, recent tsunamis have still resulted in significant casualties or unnecessary evacuations and subsequent complacency. Examples of such events include:

- February 27, 2010 M8.8[2] Maule, Chile earthquake and tsunami—156 deaths (National Centers for Environmental Information/World Data Service [NCEI/WDS], n.d.).
- March 11, 2011 M9.1 Tōhoku, Japan earthquake and tsunami—18,453 deaths (National Centers for Environmental Information/World Data Service [NCEI/WDS], n.d.).
- November 13, 2016 M7.8 Kaikoura, New Zealand earthquake and tsunami—Late threat identification, protracted warnings, inconsistent response.
- September 8, 2017 M8.2 Chiapas, Mexico earthquake—Uncertain threat resulting in protracted or unnecessary warnings that caused disruption.
- January 23, 2018 M7.9 Kodiak Island, Alaska, United States earthquake—Uncertain threat resulting in protracted or unnecessary warnings that caused disruption.

This section describes the landscape within which the tsunami emergency and risk management community currently operates and how it could be improved if tsunami warning centers were able to deliver timelier, more accurate forecasts.

Emergency Response

The Problem

Tsunamis are low-frequency, high-consequence events that can cause widespread loss of life, injuries, and physical and environmental damage and disruption. Because of the possibility of devastating impacts, tsunami warning centers and emergency management agencies treat the potential for a tsunami seriously.

As suggested in this section's introduction, a large submarine earthquake often serves as the first indicator of a potential tsunami. When such an earthquake occurs near a coast, which

[2] Where used in this paper, M denotes moment magnitude (Mw).

is the case most of the time due to the location of tectonic plate boundaries (the primary source of tsunamigenic earthquakes), warning centers have mere minutes to identify and assess the source and provide alerts before the first waves arrive. Even for communities farther away from a tsunami source, time for accurate assessments is limited as tsunamis can travel at speeds of over 800 km/h in the deep ocean.

Once a tsunami warning has been issued, community evacuation can take considerable time. So warning centers and emergency management agencies and authorities nearest an earthquake's epicenter have to act quickly and make initial warning decisions based solely on estimated earthquake location, magnitude, and depth. These preliminary assessments are inevitably relatively crude and contain a significant degree of uncertainty. For this reason, emergency managers use cautious preplanned responses as the basis for their initial decisions. This often results in under, protracted, or over warning, each of which may have negative repercussions.

It takes considerable time—often hours—after a warning is first issued before observations are made and the threat is more fully understood. This often results in cancellation of the warning, but in the interim leads to unnecessary widespread disruption, including over evacuation, economic loss, mass inconvenience, and inconsistent responses. The cumulative effect is diminished public confidence in official alerts and the responsible authorities.

The Need

For alerts to be effective, they must be timely, relevant, accurate, detailed, clear, effectively communicated, and trusted. The first three of these elements (timely, relevant, and accurate) result directly from how well the tsunami source is understood and characterized, while the remaining four elements (detailed, clear, effectively communicated, and trusted) have large dependencies on the first three. We therefore consider the first three in detail:

- **Timely:** For emergency managers and the public to be able to take timely action during a tsunami, especially a local-source tsunami, warning centers need to be able to issue a "best estimate" forecast within 5–10 min of an earthquake based on all available information.[3] To be relevant and accurate, this forecast requires a relatively high degree of certainty. However, in general, warning centers cannot provide this level of certainty within 10 min due to current challenges related to tsunami source characterization and observational gaps noted in this paper's introduction.
- **Relevant:** From an emergency management perspective, relevance is determined by the nature and extent of the tsunami threat, which may range from strong currents and anomalous ocean conditions to significant land inundation. The decision to issue alerts and the associated advice and instructions must therefore be relevant to each situation. For example, if inundation is forecast, instructions to immediately evacuate to high ground may be appropriate. Alternatively, if strong currents are anticipated but there is not a perceived threat to land, a notice advising caution in and around the water may suffice. In response to a potential tsunami threat, emergency managers need to decide what actions to take and the instructions to issue to their constituents, if any. Existing forecast uncertainties complicate these decisions.
- **Accurate:** When a tsunami threatens, emergency managers and the supported public require a forecast that accurately identifies the scope and scale of the event and associated alert level(s). Accurate forecasts can help communities avoid unnecessary disruption while at the same time ensure response resources are directed and focused on the most at-risk areas. Forecast accuracy is particularly important in urban areas and tourist destinations, where overestimating the threat can strain the usually limited emergency management resources available at short notice and cause ancillary safety concerns. Currently, warning centers, in general, are not able to provide enough information about the level or extent of inundation within the desired time frame (i.e., within 5–10 min of event origin) to support effective response.

Application of More Timely, Higher Certainty Forecasts

The quality of public alerts largely depends on the three elements described in the previous subsection. Once the challenges to these elements are overcome, emergency managers will be confident that during a tsunami they will receive information in a timely manner and with a degree of certainty that supports decision-making. This confidence will enable them to refine their planning and procedures to support better responses. They will be able to tailor public alerts to the required level of detail and provide enough specificity in their instructions. Effective alerts, in turn, will enhance public and political confidence in the responsible authorities, underpin successful community response, and, ultimately, save lives.

Nevertheless, albeit to a lesser degree, some uncertainties will remain. Emergency managers and the public will need to be made aware of these uncertainties so they can consider them in their decision-making.

Tsunami Risk Management

What we know about tsunamis is important for managing the risk before disaster strikes. Tsunami hazard and risk assessment (e.g., inundation and evacuation modeling) depends on scientific information, and even the most sophisticated scientific knowledge has some degree of uncertainty. This does not mean the information is unreliable, but this uncertainty strongly influences the risk management process.

Risk management is by its very nature about managing uncertainty. Decision makers have been writing policy, developing management frameworks, and issuing advice to protect at-risk communities for a long time based on limited information or uncertain hazard and risk assessments.

Addressing uncertainty associated with tsunamis extends beyond emergency response. Better characterization of tsunami

[3]The 5–10 min target does not negate the need to continue outreach and education efforts focused on natural warnings, which are the primary warnings for local-source tsunamis. Natural warnings include strong or long earthquake shaking, a sudden rise or fall of the ocean, and unusual ocean sounds.

sources is an important preparedness activity that, once fully realized, will contribute to a better understanding of the risk from local-, regional-,[4] and distant-source tsunamis. This will allow for risk-informed decision-making in all aspects of emergency management.

In 2011, the Tōhoku, Japan earthquake and tsunami exceeded the previously recognized level of risk. Despite the region's high level of tsunami preparedness, the tsunami protection measures (e.g., barriers and evacuation planning) were insufficient (Mori et al., 2011; Suppasri et al., 2012). This event clearly illustrates the high degree of uncertainty that still exists in tsunami hazard and risk assessments used for pre-event decision-making. As such, emergency management and monitoring agencies have to acknowledge and accommodate uncertainty in their tsunami response planning activities.

End-to-End Benefits of Reducing Uncertainty

In summary, while our understanding of tsunamis will continue to evolve and challenge how we detect and measure tsunami sources and forecast the resulting waves, it is important to acknowledge that 100% certainty may never be achieved. Still, coordinated efforts to deliver more accurate tsunami impact forecasts would fundamentally improve the end-to-end tsunami risk and emergency management system. Benefits include the following:

- More decisive and effective public response to emergency management direction: Consistently demonstrating that emergency management instructions are appropriate and based on high-confidence forecasts can instill confidence in the public to act decisively when a tsunami threatens.
- More refined tsunami hazard and risk assessments linked to tsunami forecasts: A key requirement for effective preparedness and disaster reduction is an understanding of how a tsunami will impact individual coastlines before it strikes.
- Improved community preparedness: Refined, accurate tsunami inundation and evacuation modeling through better-informed scenario simulations can support actions before and after a tsunami emergency.
- Strengthened public education programs and messaging: The more that is known about potential tsunami impacts, the better education programs and action messages can be tailored to ensure official messages are relied on as trusted and accurate.
- Assured governments and policy makers: More confidence and certainty provide transparency and trust when decisions on processes, policies, plans, risk management frameworks, or investments depend on reliable, risk-based information.
- Increased investment in risk reduction, ocean-based science research, and targeted mitigation strategies: The prospect of reduced uncertainties associated with tsunami forecasts may make research sponsors more likely to support tsunami-focused applications and broader sea-level-related activities.

The Sendai Framework for Disaster Risk Reduction

Focusing on reducing tsunami forecast uncertainty also supports the goals and intentions of the Sendai Framework for Disaster Risk Reduction[5] (agreed to internationally by Member States). Specifically relevant is "Target G: Substantially increase the availability of and access to multi-hazard early warning systems and disaster risk information and assessments to the people by 2030." The framework aims to achieve "substantial reduction of disaster risk and loss to life, livelihoods and health, and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries." Key components of Target G focus on improved detection, monitoring, analysis, and forecasting of hazards and possible consequences, and dissemination and communication, by an official source, of authoritative, timely, accurate, and actionable alerts and associated information on likelihood and impact (United Nations International Strategy for Disaster Reduction [UNISDR], 2015).

ADDRESSING TSUNAMI DETECTION, MEASUREMENT, AND FORECASTING UNCERTAINTIES

In 2004, the tsunami threat in the Pacific was acknowledged and much better understood than in the Indian Ocean given its recent history of large tsunamis and basin-wide warning system. At that time, tsunami forecasts and alerts were most effective for distant-source tsunamis, were based primarily on preconceived assumptions and historical analogs, and were very broad-brush, which often resulted in over warning. Advancements since 2004 include methods for better tsunami source characterization (mainly through more sophisticated seismic analysis) that in combination with faster numerical tsunami forecast models and denser sea-level observation networks significantly improved the global tsunami warning and mitigation system's distant-source tsunami capability.

The opportunity now exists to greatly enhance this capability and to produce more accurate, near-real-time inundation forecasts for local-source tsunamis. In this section, we describe recent and coming advances that could result in fundamental improvements to the ability to more rapidly and accurately constrain tsunami sources, thereby greatly reducing tsunami forecast errors. Of course, no technique for characterizing tsunamis stands alone. The observation systems we currently collectively leverage, or plan to, are listed in **Tables 1A,B** and discussed in the following subsections.

[4] A regional-source tsunami is between 1 and 3 h tsunami travel time away.

[5] Information about the Sendai framework is online at https://www.unisdr.org/we/coordinate/sendai-framework.

TABLE 1A | Observation utility matrix: Geophysical and atmospheric measurements.

Type of observation	**Preparedness**	**Tsunami warning**							**Assessment**	**Other scientific uses**
(measured and inferred parameters)	**Risk assessment and planning**	**Generation**		**Verification**		**Forecast**		**Termination**	**Post-event analysis**	
		Earthquake characteristics and potential tsunami generation	Earthquake characteristics and early warning for local tsunamis	R/T deep-ocean sea-level monitoring and verification	R/T coastal sea-level monitoring and verification	Deep-ocean forecast and warning	Coastal impact forecast and warning	Warning cancellation		
Bathymetry (water depth, seafloor shape)	x					xx	xx		x	Ocean and coastal forecasting, storm surge inundation, tide predictions
Seismic station (earthquake magnitude, location, depth)	x	xx	x			xx	x		x	Earthquake monitoring, Comprehensive Nuclear Test Ban Treaty
GNSS (earthquake magnitude, location, rupture characteristics)	xx	x	xx			x	x		x	Earthquake and tectonic plate monitoring, sea-level variability and change monitoring
Infrasound array (atmospheric pressure, verify tsunami generation)		o	o			o	o	o	x	Atmosphere monitoring, defense
Ionospheric perturbation (internal atmospheric gravity waves)		o	o	o		o	o	o		Interference to global communication systems and technologies

x, use; xx, main use; o, assuming data is available and can be analyzed in real-time; R/T, real-time.

TABLE 1B | Observation utility matrix: Oceanographic measurements.

Type of observation	Preparedness	Tsunami warning							Assessment	Other scientific uses
(measured and inferred parameters)	**Risk assessment and planning**	**Generation**		**Verification**		**Forecast**		**Termination**	**Post-event analysis**	
		Earthquake characteristics and potential tsunami generation	Earthquake characteristics and early warning for local tsunamis	R/T deep-ocean sea-level monitoring and verification	R/T coastal sea-level monitoring and verification	Deep-ocean forecast and warning	Coastal impact forecast and warning	Warning cancellation		
Tsunameter (bottom pressure, sea-level height)	x	x		xx		xx	x	x	x	Ocean monitoring and forecasting, seafloor ocean pressure
Cable observation system (bottom temperature and pressure, sea-level height)	x	xx	xx	xx	xx	xx	x	x	x	Ocean monitoring and forecasting, seafloor properties
Satellite altimeter (sea-level height anomalies)	x			o	o	o	o	o	xx	Ocean forecasting, sea-level monitoring
Coastal sea-level station (sea-level height, local atmospheric conditions)	x	x	x		xx	x	xx	x	x	Tide predictions, sea-level variability and change monitoring, ocean and coastal monitoring and forecasting
Coastal high-frequency radar (wave, current, wave energy)	x	x			xx		xx	x	x	Ocean and coastal monitoring and forecasting

x, use; xx, main use; o, assuming data is available and can be analyzed in real-time; R/T, real-time.

Inferring Tsunami Source Parameters From Solid-Earth Measurements

If key tsunami source parameters, including generating mechanisms, are known, then a tsunami can be computed with reasonable accuracy. Most often, the mechanism is vertical displacement of the sea over a large area caused by an earthquake. To accurately forecast tsunami impacts at the coast following a large earthquake, warning centers need to estimate how the earthquake deformed the seafloor. Tsunami forecast models can then simulate tsunami propagation toward coastlines and guide warning decisions. Model guidance can also inform decisions for coasts that should be unaffected, allowing activities there to proceed without disruption.

Outside of a few limited areas, there are currently no practical ways to directly measure earthquake-induced seafloor displacement. It must be inferred from other data. Procedures for approximating a tsunami source from an earthquake's seismic signals have evolved over many decades.

Today, seismic waves can be analyzed quickly to determine an earthquake's preliminary location and depth (hypocenter), magnitude, and origin time. Assuming an earthquake ruptures with the same mechanism as past large earthquakes in its hypocentral region, the rupture is largely uniform across the fault, and the hypocenter represents the center of the rupture, seafloor deformation can be estimated. However, this initial estimation has large uncertainties because the actual fault mechanism may be different, the rupture may not be uniform, the earthquake may propagate along the fault, and the hypocenter may not be where the main rupture initiated. These uncertainties are even more typical and problematic for very large events (i.e., those greater than M8.6).

Research aimed at better inferring fault and rupture planes using seismic analysis is promising, but implementation is not currently widespread. Even when these improved rapid seismic assessment techniques are applied, significant initial uncertainties will remain, so tsunami forecasts based solely on this type of analysis must be used with caution.

Additional seismic analysis normally produces a centroid moment tensor (CMT)—the first indication of an earthquake's mechanism—in 20–30 min. For earthquakes with moment magnitudes[6] from the M7s to lower M8s, the CMT information is usually sufficient to estimate seafloor deformation for tsunami forecast purposes. In most cases, the fault ruptures of these earthquakes are not so large (a few tens to a couple hundred kilometers) that rupture disparities significantly affect tsunamis.

However, for the largest earthquakes, ruptures measure from hundreds to more than a thousand kilometers. For these events, the aforementioned seismic analyses are inadequate. They do not describe earthquake complexities (e.g., homogeneous vs. complex slip distribution) with enough detail to accurately reproduce a tsunami in a forecast model in a timely manner, particularly in the near field. Hébert et al. (2007) and Hébert and Schindelé (2015) showed that for regional- and distant-source tsunamis, wave height estimates based on an homogeneous source could be as much as two to three times different than those based on a complex slip distribution source.

Therefore, new data and methods—seismic and non-seismic—are needed to more precisely characterize rupture complexities of very large earthquakes within a few minutes to produce more accurate tsunami forecasts from numerical models.

Seismic Analysis

Earthquakes generate more than 80% of all tsunamis worldwide (National Centers for Environmental Information/World Data Service [NCEI/WDS], n.d.) and are responsible for the majority of deadly tsunamis in recorded history. Seismology provides the first indication that a potentially tsunamigenic earthquake has occurred. Seismic waves travel much faster than tsunami waves, and the dense global network of seismic stations enables detection and location of most tsunamigenic earthquakes within about 5 min, anywhere on Earth.

Once a potentially tsunamigenic earthquake is detected, warning centers aim to disseminate tsunami forecasts as soon as possible. Numerical forecast models rely on the estimation of seafloor displacement (Okada, 1985) or measurement of sea-level changes. Since direct measurements are not available in the early stages of an event, seismological proxies of seafloor uplift based on analysis of fault location, size, and type are used to infer those changes and drive initial forecasts.

Thus, the seismic source must be characterized as soon as possible. This process currently involves the following:

- **Stage 1 (0–5 min):** Detection of earthquake: First indication of tsunamigenic potential based on limited observation. Initial seismic analysis, including very uncertain estimates of size (magnitude), location, and tsunamigenic potential.
- **Stage 2 (5–10 min):** Confirmed basic earthquake parameters: Improved estimation of location, depth, and size (magnitude) based on enough observations to begin to decrease the uncertainty of tsunamigenic potential. Initial issuance of tsunami alerts using assumptions of earthquake type based on the source region's tectonics is possible.
- **Stage 3 (20–30 min):** Improved seismic source parameters: Source characterization, including good estimates of location, depth, size (moment), fault angles (strike, dip, rake), type (strike-slip, normal, or reverse), and slowness, but not extent or rupture details. This allows generation of the first reliable tsunami forecasts.
- **Stage 4 (hours to days):** Full characterization of seismic source rupture parameters: including location, depth, size (width, length), fault angles and type, geometry, extent, and rupture details, including amount and variation of slip. This allows generation of very reliable tsunami forecasts.

After these stages, seismological uncertainty is as low as possible. Any further significant reduction of uncertainty requires dedicated research.

Although the stages are sequential, the total elapsed time is what matters most. This is where research can deliver large gains. The challenge is to get to Stage 4 much more quickly. The suggested maximum elapsed time is as close to 5 min as possible,

[6]See **Appendix** to learn more about moment magnitude.

but the target for the next decade is 10 min (Intergovernmental Oceanographic Commission [IOC], 2018). This target is unlikely to be met using seismology alone. However, use of seismology in combination with other techniques and technologies [see section "Global Navigation Satellite System (GNSS)"] can be a major factor in reducing tsunami source uncertainty.

Nevertheless, in the last decade, huge advances have been made in seismic analysis techniques used to describe earthquake source parameters more accurately and with greater speed, and this trend is expected to continue. Examples of developing techniques include the use of strong-motion centroid and seismic energy back-projection techniques, which can be used to provide better estimates of the size and geometry of an earthquake's rupture. **Appendix** contains more information and references about these developments and other examples of seismic analysis techniques and developments being applied to quickly determine an earthquake's tsunamigenic potential.

Global Navigation Satellite System (GNSS)

A large number of GNSS stations currently produce continuous positions for many purposes. Of these stations, an estimated 3,500 could support tsunami warning by helping forecasters infer seafloor displacement in real time (Timothy Melbourne, personal communication, June 5, 2018) (see **Figure 2**). Location and data availability are key constraints on the usability of these stations for this purpose. To use GNSS data to characterize tsunamigenic earthquakes, stations must be near potential tsunami sources. While a significant number of stations are used for tectonic research, not all currently report in real time. To be useful for tsunami warning purposes, GNSS stations typically feature a 1-Hz sampling rate with a delay in the transmission of processed data of approximately 5 s.

Several tsunami warning centers are currently investigating use of GNSS-derived earthquake magnitudes and other fault parameters. The initial focus of the United States warning centers is on the Cascadia subduction zone, the potential source of a large earthquake that would have the greatest tsunami impact on United States and Canadian coasts. Once fully implemented, this methodology could be extended to other tsunami source zones where GNSS data exist.

If significant numbers of useable GNSS stations are near a fault zone, then it is possible to produce a finite fault model for an earthquake within a few minutes. Such a model would fully describe the fault parameters, providing spatial detail on the fault geometry and amount of slip and enable seafloor displacement to be inferred. This represents one of the few ways to achieve a very high level of forecast certainty before sea-level measurements are available. Thus, a combination of advances in seismic analysis and GNSS techniques is likely to significantly improve the tsunami warning process in the near future.

The use of GNSS data to derive a seismic source necessary for tsunami forecasting is expected to proceed in three steps. During Step 1, an estimate of earthquake magnitude will be computed based on ground displacement (peak ground displacement magnitude, Mpgd) and hypocenter location. The Mpgd technique has demonstrated it is capable of consistently producing quick and accurate magnitude estimates for earthquakes larger than M6.0 (Melgar et al., 2015).

Step 2 will be initiated before completion of Step 1. In Step 2, static offset measurements reported by GNSS stations will be used to compute a CMT solution that contains information about the earthquake's focal mechanism. This information is vitally important for determining the earthquake's tsunamigenic potential. Steps 1 and 2 are expected to be completed 2–3 min after first rupture.

Step 3 is also based on the use of GNSS static offsets. It involves performing a non-uniform slip inversion over the region after the CMT solution is generated. The inversion that best fits observations is the preferred solution. The results of this type of analysis, called a finite fault solution, are particularly relevant for earthquakes with slip distributions concentrated on the shallow part of the fault since they have the most potential to generate large tsunamis not adequately captured by the overall CMT solution.

In most cases, Steps 1, 2, and 3 are performed almost simultaneously, and the respective solutions are expected to become available only seconds apart. There may be situations, however, in which an Mpgd solution with an assumed focal mechanism based on a historical catalog of events may be more accurate than a real-time CMT or finite fault solution if the number of available GNSS stations is small.[7]

Measuring Tsunamis in the Deep Ocean

Even with a well-constrained seismic solution, the correlation to a tsunami is not absolute (Titov et al., 2016). Tsunami parameters are uncertain until direct measurements are available. Typically, these measurements come from bottom pressure sensors contained in a BPR.[8]

Bottom Pressure Recorders

Deep-ocean BPRs provide direct detection and measurement of tsunamis. These instruments sit on the seafloor and communicate with surface buoys to transmit data in real time. Since the deep-ocean tsunami signal is not contaminated by coastal processes that typically affect coastal sea-level stations, these deep-ocean measurements are invaluable for tsunami warning decision-making and direct verification of tsunami modeling accuracy.

Traditionally, BPRs have been placed on the seafloor as part of discrete, widely spaced buoy systems. Developed by the U.S. National Oceanic and Atmospheric Administration (NOAA), Deep-ocean Assessment and Reporting of Tsunami (DART) buoy systems constituted the first operational network of instruments designed to measure tsunamis in the deep ocean (Bernard and Meinig, 2011; Rabinovich and Eblé, 2015) (see **Figure 3**). DART systems and similar deep-ocean observation buoy systems are

[7] It should be noted that while a single GNSS station can be sufficient for estimating the Mpgd of a seismic event, the need for a sufficiently high signal-to-noise ratio limits the allowable distance between the recording station and the epicenter. This minimum distance will vary with the magnitude of the event, but if one considers only events larger than Mw 7 to be of tsunamigenic interest, then the estimated minimum distance for Mpgd estimation is approximately 200 km (Brendan Crowell, personal communication, March, 2019).

[8] This paper uses "bottom pressure recorder," but it is synonymous with other terms, including "ocean bottom pressure gauge."

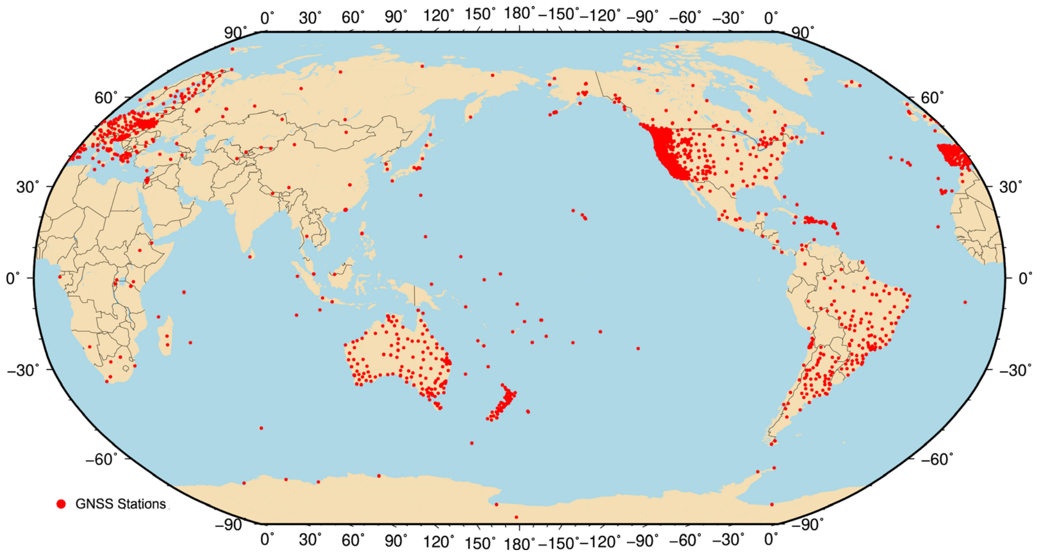

FIGURE 2 | This map illustrates the location of 2,260 real-time GNSS stations from public networks around the world. GNSS stations in non-public networks (e.g., in Japan, Mexico, and Chile) are not shown here but could also support tsunami warning. Source: Pacific Northwest Geodetic Array/Central Washington University.

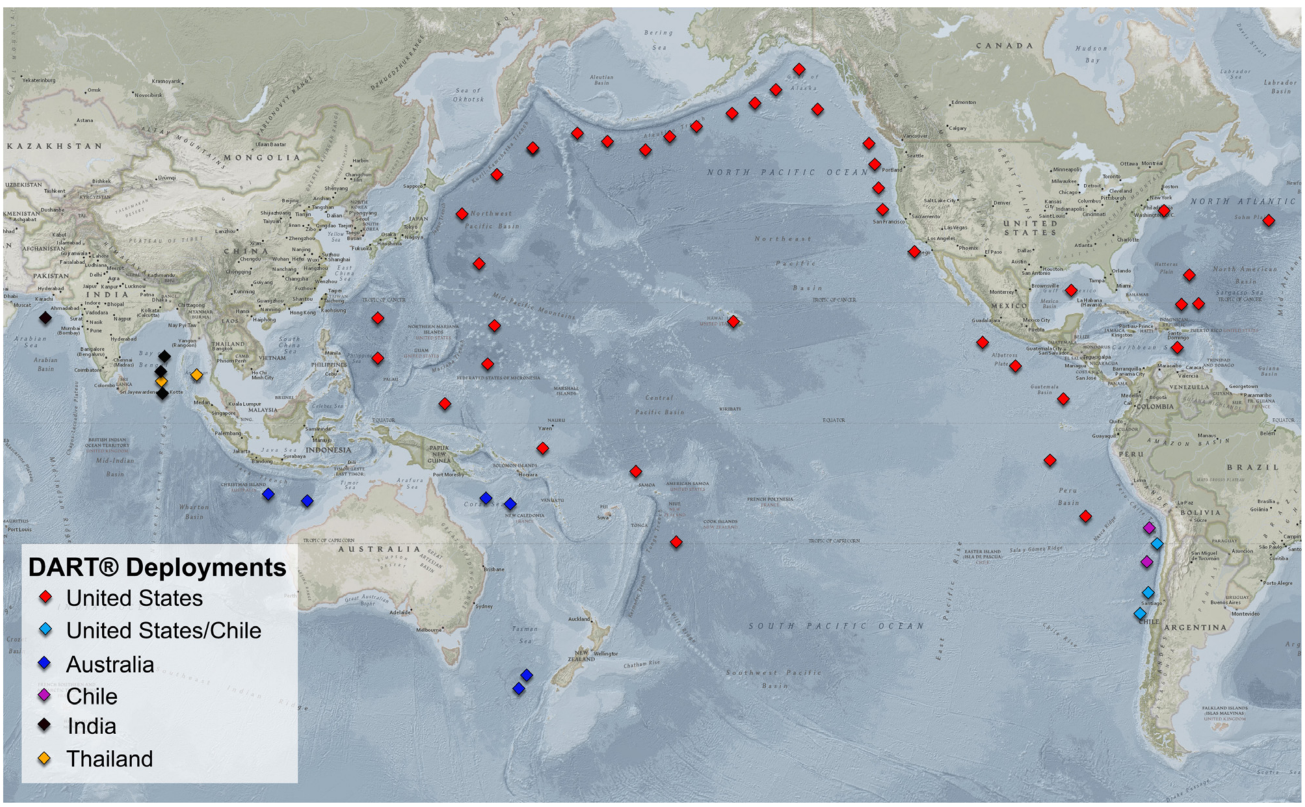

FIGURE 3 | This map provides a visual summary of the DART system network as of November 2018. The DART network includes United States systems as well as systems owned and operated by Australia, Chile, India, and Thailand. Source: Adapted from NOAA National Centers for Environmental Information.

made by a number of manufacturers and are generally called tsunameters. Today, more than 60 individual tsunameters are deployed worldwide.

Dedicated undersea cabled observation systems that link BPRs have been successfully installed in Japan, Canada, and the United States and represent a major step forward in early tsunami detection and measurement (Rabinovich and Eblé, 2015). Even more promising is the opportunity to leverage the network of transoceanic fiber-optic submarine telecommunications cables, which are continually refreshed and expanded on 10–20 year cycles. By equipping these cables with environmental sensors such as BPRs and accelerometers, we could see major improvements in the ability to rapidly detect and measure tsunamis in the open ocean (You, 2010; Butler et al., 2014; Howe et al., 2018).

It is important to note a recent development that will likely lead to deployment of more BPRs, some suitable for tsunami warning purposes. A new *in situ* calibration method has been devised that largely removes sensor calibration drift, reducing it from tens of cm/year to ∼1 mm/year (Wilcock et al., 2017). This development will likely lead to deployment of bottom pressure sensors to monitor ocean circulation and for long-term climate monitoring purposes (Pugh and Woodworth, 2014; Hughes et al., 2018).

Tsunameters

A tsunameter is composed of a surface buoy that contains communications packages and a BPR that measures the pressure on the seafloor created by the weight of the water column above it. A tsunameter can detect and measure tsunamis as small as 1 mm in 6,000 m of water. As tsunami detectors, tsunameters have a number of advantages over traditional coastal sea-level stations:

- Tsunameters are deployed in the deep ocean, far from coastlines that can generate local wave reflections, trapping, local resonance, and other effects, which tend to obscure an original tsunami signal.
- Deployment of tsunameters on the offshore (deep ocean) side of a trench takes advantage of faster deep-ocean propagation speeds, making it possible to record a tsunami signal at a tsunameter before it arrives at a coastal sea-level station.
- Tsunameters support the use of linear inversion techniques (Percival et al., 2009). This allows for much more accurate tsunami source reconstruction than is possible from coastal sea-level station data.
- Tsunameters naturally filter wind waves and other high-frequency noise out of the pressure signal (i.e., mechanical filters or post-processing are not required). This results in a higher quality signal-to-noise ratio, which is key to tsunami detection.

The time it takes a tsunameter to detect a tsunami is based on proximity of the BPR to the tsunami's source. However, since seismic and tsunami waves are both generated in the source region, most tsunameters are deployed a sufficient distance away from the source to reduce overlap of seismic and tsunami signals. Given the differential in their propagation speeds (∼3 km/s for seismic waves, ∼0.2 km/s for tsunami waves), the waves ultimately separate naturally. Nonetheless, this is a limiting factor in tsunameter positioning as it introduces a time delay of approximately 20–30 min between earthquake origin and tsunami detection (Mofjeld, 2009).

The latest generation of DART systems (DART 4G) is designed to address this latency problem (Meinig et al., 2001; Bernard and Meinig, 2011). DART 4G systems feature a higher sampling rate (1 Hz) than previous generations, which allows for the resolution of both seismic and hydrodynamic waves. The new systems then apply a low-pass filter to the total signal, filtering seismic noise from the tsunami waves. This allows positioning of BPRs much closer to sources (e.g., a subduction zone), eliminating the need to wait for the seismic and hydrodynamic signals to separate naturally.

Cabled observation systems

Connecting BPRs by dedicated undersea cabled observation systems is another way to monitor offshore tsunamis with accuracies equal to or better than stand-alone systems. Because the data-transmission delay is less than 1 s, observation data are available in real time.

A significant advantage of cabled observations is the ability to continuously supply a large amount of power to BPRs since they are connected to land stations through the cable. This allows a constant stream of high-sample-rate data to warning centers. Also, since BPRs are on the seafloor and require no ocean surface communication links (unlike tsunameters), accidents and theft are unlikely. Dense arrays are possible and have been implemented in Japan, as described below, as well as Canada and the United States. The primary infrastructure of these systems is based on submarine telecommunications cabled systems with extremely high reliability (one failure in 25 years).

The disadvantage is the high capital cost. To mitigate this, BPRs must be made as reliable as the basic infrastructure and/or multiple BPRs must be deployed for redundancy and to minimize maintenance costs. Regardless, cabled observation systems likely have lower lifetime costs than alternatives, e.g., buoy-based, ship-maintained systems.

The 2011 Tôhoku, Japan earthquake and tsunami reaffirmed the need for BPRs in Japan. To improve the observation network, the National Research Institute for Earth Science and Disaster Prevention (NIED) installed the Seafloor Observation Network for Earthquakes and Tsunamis along the Japan Trench (S-net) off the Pacific coast of east Japan (Kanazawa, 2013). S-net consists of 150 tsunami observation modules hardwired into the system, five landing stations, and connecting cables providing coverage for the coast and the seafloor near the trench. When fully operational, it is expected that S-net will allow tsunami detection and characterization 25 min earlier than without it.

In addition, the Japan Agency for Marine-Earth Science and Technology installed the Dense Oceanfloor Network System for Earthquakes and Tsunamis (DONET) off the Pacific coast of southwest Japan (Takahashi et al., 2017) (see **Figure 4**). Operated by NIED, DONET consists of 51 tsunami observation modules with plug-and-play nodes and landing stations (Kaneda, 2013).

During a tsunami, data collected by these cabled observation systems are sent to the Japan Meteorological Agency (JMA), which is responsible for issuing tsunami alerts.

Similar systems, though smaller scale, are deployed in Canada (North East Pacific Time-series Underwater Networked Experiments, or NEPTUNE) and the United States (Ocean

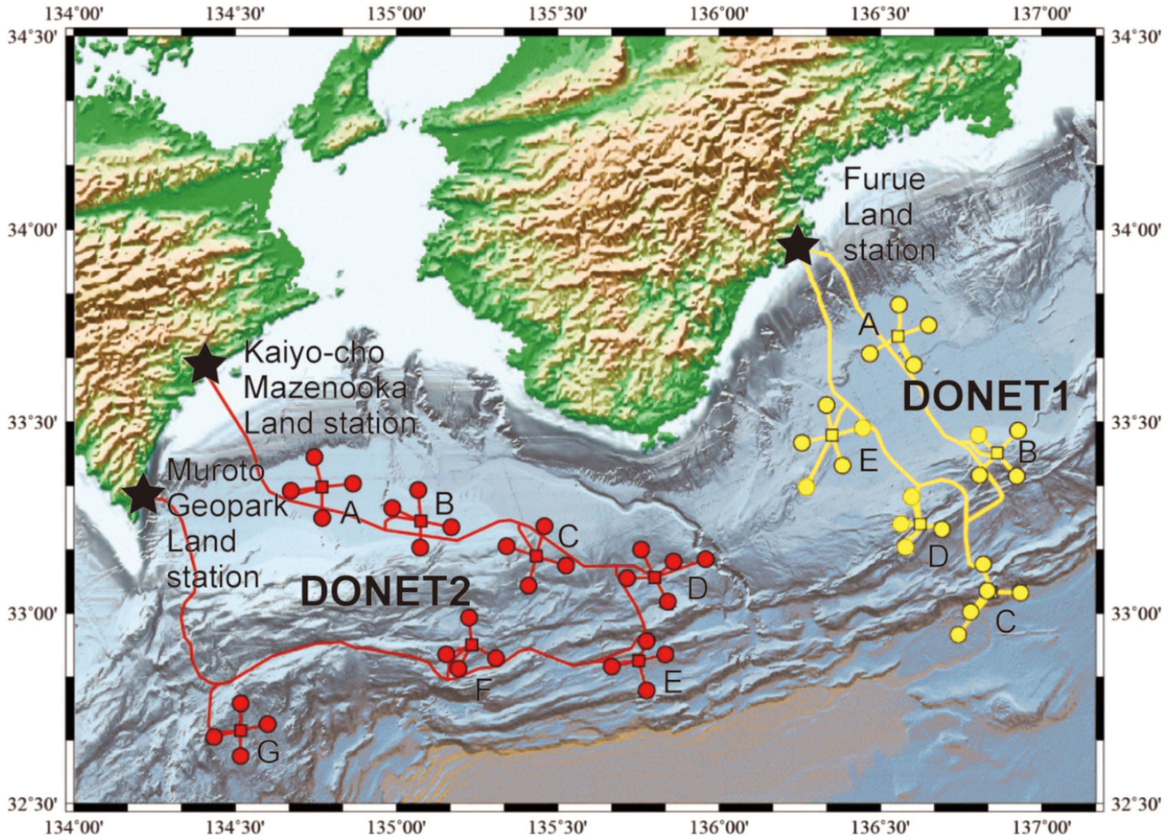

FIGURE 4 | Map of DONET installation. DONET1 and DONET2 observatories are shown with yellow and red circles, respectively. Stars are land stations. Letters indicate nodes (branching apparatuses). Source: Adapted from Takahashi et al. (2017).

Observatories Initiative) (Thomson et al., 2011; Rabinovich et al., 2013; Fine et al., 2015). The U.S. National Tsunami Warning Center is using some of the data from these systems in its forecast and warning operations.

Though effective, due to the costs, it is unlikely that tsunami-dedicated cabled observation systems will ever cover a significant percentage of the world's tsunamigenic regions. To address this, the International Telecommunication Union, the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (IOC/UNESCO), and the World Meteorological Organization established a Joint Task Force in 2012 to develop and implement the Science Monitoring and Reliable Telecommunications (SMART) cable initiative.

The goal of the SMART initiative is to integrate scientific sensors for ocean and climate monitoring and disaster risk reduction, including tsunamis, into the repeaters of new fiber-optic telecommunications cables (Howe et al., 2016; Tilmann et al., 2017). Over the normal one- or two-decade refresh cycle for such systems, global coverage could be built up. If industry and government would instrument their fiber-optic cables with BPRs and accelerometers, particularly in locations important for tsunami detection, it would greatly improve the world's ability to rapidly detect and measure tsunamis (Butler et al., 2014; Barnes et al., 2016; Ranasinghe et al., 2017; Barnes, 2018). **Figure 5** illustrates the proximity of existing cable networks to tsunami source areas and existing tsunameters.

A new distributed sensing technology based on using optical fibers themselves as sensors is also in development. A particularly attractive application includes using a combination of forward transmission optical interferometry and absolute time measurement (Marra et al., 2018) to passively use existing transoceanic fiber-optic cables as a continuously distributed ground deformation sensing network from which seismic or bottom pressure information could be inferred.

Measuring Tsunamis at the Coast

Real-time tsunami observations at the coast are essential for reducing associated tsunami forecast uncertainties and will become more important as techniques to better characterize tsunami sources emerge. Coastal observations are an important means of:

- Verifying tsunami generation and validating the need for alerts,
- Providing information on the actual coastal response to deep-ocean propagating tsunamis,

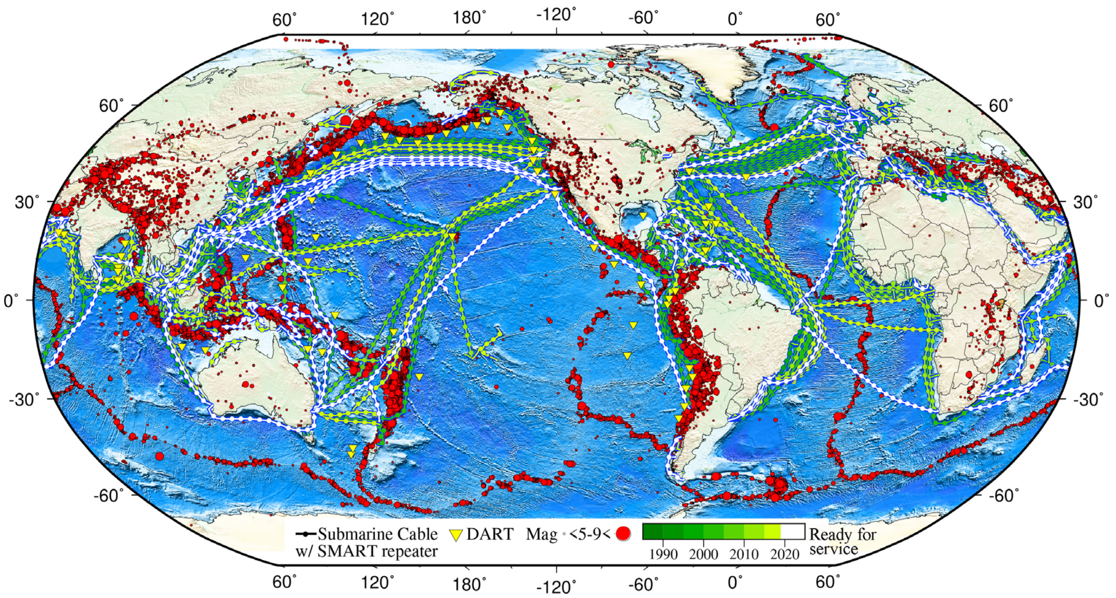

FIGURE 5 | Current and planned submarine cables, locations and magnitudes of historical seismic events, and the existing tsunameter network. Environmental sensors (pressure, acceleration, temperature) can be added to the cable repeaters every ∼100 km, gradually obtaining real-time global coverage (for clarity, repeaters are shown only every 300 km). Map by M. Chandler using GMT. Cable data: TeleGeography's Telecom Resources licensed under Creative Commons ShareAlike. DART system data: NOAA National Data Buoy Center. Seismic data: United States Geological Survey Earthquake Catalog.

- Constraining deep-ocean propagation and coastal inundation forecasts,
- Monitoring tsunami propagation across impacted ocean basins,
- Monitoring tides and their addition to or subtraction from tsunami-induced sea-level changes,
- Enabling cancellation of tsunami alerts,
- Guiding local emergency management decision-making regarding "all clear" advice,
- Validating tsunami forecast models in real time,
- Improving forecast accuracy for future events, and
- Evaluating long-term tsunami risk for planning purposes.

Coastal observations of tsunamis are also important for historical record keeping. This informs hazard and risk assessments that help identify at-risk communities and supports community education and preparedness.

Coastal Sea-Level Stations

Sea-level stations have long been used to monitor sea level at the coast to prepare tide predictions at prescribed locations for maritime navigation (Pugh and Woodworth, 2014). They have also proven valuable in documenting sea-level variability and the rate of sea-level change relative to land benchmarks (Church and White, 2011).

Coastal sea-level data that are distributed in real time are extremely valuable for the tsunami warning process, in particular for the verification of tsunami generation and impact on local sea level (see **Figure 6**). This is especially true as techniques are developed to improve tsunami forecast accuracy through faster source characterization. As modeling and computing capabilities continue to evolve, it may be possible to use data from coastal sea-level stations to further constrain tsunami sources, thereby improving tsunami forecasts, including inundation.

Sea-level data have played an important role in the reduction of forecast uncertainties associated with complex bathymetry (Sahal et al., 2009; Vela et al., 2014). In the Pacific, several decades of tsunami records have allowed the application of specific amplification factors at locations with coastal sea-level stations (Jamelot and Reymond, 2015). In these cases, results compare favorably to those obtained by applying a modified Green's law; observed amplitudes then normally show errors of a factor of less than two.

Elsewhere, where there are no records of tsunamis at coastal sea-level stations, coastal amplification factors have been derived by comparing nested-grid modeling output to modified Green's law results (Gailler et al., 2018). This method is best suited for small basins like the Mediterranean and Caribbean and near-field coastlines, where nested-grid computations are not feasible in real time.

Once a tsunami alert is issued, warning centers use sea-level data to update (i.e., downgrade, upgrade, expand, narrow) or cancel it. Below are examples of coastal sea-level station observations that influenced tsunami messages.

- On January 10, 2018, an earthquake with an original magnitude of 7.8 registered in the Northwest Caribbean. Within 5 min, the Pacific Tsunami Warning Center (PTWC) issued tsunami messages to its partners in the region. Because of the lack of sea-level data in the epicentral region, it took almost 1 h to confirm tsunami generation, but it was very small and was not a threat. Soon

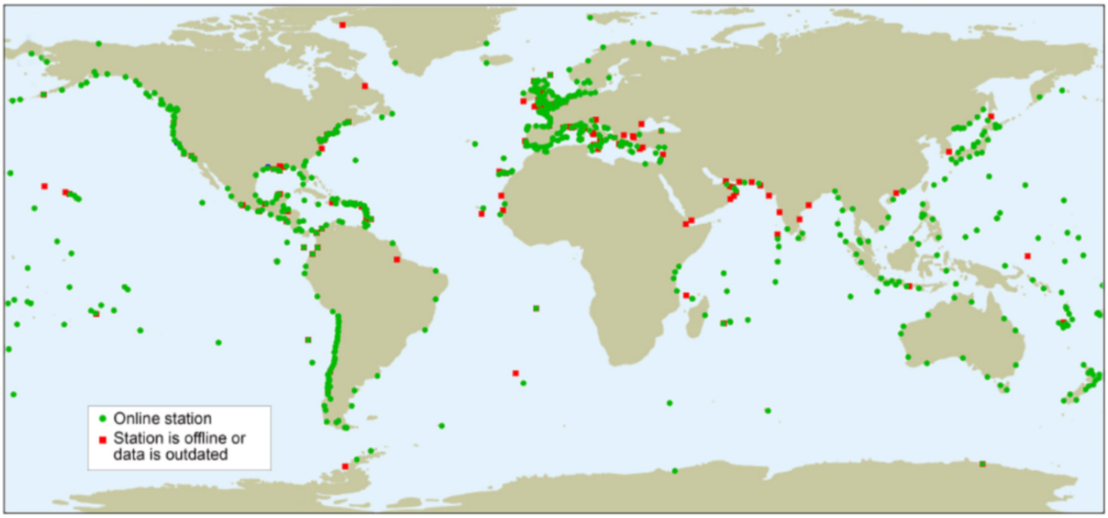

FIGURE 6 | Coverage of available real-time coastal sea-level data (green dots) as of February 2019. (Red dots indicate data outages.) Note large gaps around the world where data is not available in real time. Source: IOC/UNESCO Sea Level Station Monitoring Facility.

after, the PTWC issued its final messages for the event. A shorter detection time would have reduced the anxiety and actions observed.

- For the M8.6 North Sumatra, Indonesia event of April 11, 2012, and the M7.8 Southwest Sumatra, Indonesia event of March 2, 2016, since the earthquakes were far away from the main fault lines and there were no precomputed scenarios, the Joint Australian Tsunami Warning Centre (JATWC) issued precautionary advice for parts of Australia near the sources in the Indian Ocean. The waves observed at nearby coastal sea-level stations did not meet warning-level criteria, so the JATWC downgraded and then cancelled the alerts as soon as possible to avoid further unnecessary actions from emergency services and the public.
- In the M7.9 Solomon Islands event of February 6, 2013, the JATWC correctly notified the public that there was no threat based on observations from coastal sea-level stations. The continued monitoring of coastal sea-level station data as waves formed and propagated toward Australia helped confirm the accuracy of the original decision as the sea-level anomalies did not meet the criteria for an actionable alert. Coastal sea-level stations from the Solomon Islands to Vanuatu to Australia's Rosslyn Bay recorded these anomalies.
- In the M8.4 Coquimbo, Chile event on September 16, 2015, the availability of 40 coastal sea-level stations in contrast to the 20 stations available for the M8.8 Maule, Chile event on February 27, 2010, led to more effective messaging and response.

Other Emerging Techniques for Detecting and Measuring Tsunamis

There are a number of other instruments or applications developed for, or capable of, gathering information that can be helpful in detecting and measuring tsunamis. While the following techniques are not expected to support the immediate goal of precise real-time tsunami measurement or source characterization, they are of promising value for event reconstruction (satellite altimetry), confirming tsunami generation (ionospheric perturbations and infrasound), and detecting tsunamis in surface wave reflections (coastal radar).

Satellite Altimetry

The use of satellite altimeters to measure and analyze changes in sea level has been successfully demonstrated following recent tsunamis such as the 2004 Indian Ocean and 2011 Tōhoku, Japan tsunamis (Gower, 2005; Smith et al., 2005; Hébert et al., 2007; Song et al., 2012). Satellite altimeter data are direct measurements of changes in sea level. Consequently, the process to constrain a tsunami source from these data is very similar to that currently employed with tsunameter data by some operational forecast systems.

Satellite altimetry has the advantage of providing both spatial and temporal variation not present in the static time series reported by tsunameters. As a case in point, a number of researchers used sea-level data collected by the Topex-Poseidon, Envisat, and Jason 1 missions processed after the 2004 Indian Ocean tsunami to constrain tsunami initial conditions and model propagation throughout the Indian Ocean (Gower, 2005; Smith et al., 2005; Hébert et al., 2007). Seismologists also used altimetry data to complement seismic observations in characterizing the 2004 earthquake's source (Geist et al., 2007).

Disadvantages associated with this technology include limitations in sensitivity, limited satellite coverage, and extended data processing times (especially for small tsunamis). Thus, operational use of satellite altimetry in real-time tsunami forecasting is not currently a viable solution.

Ionospheric Perturbations

Tsunamis also create disturbances in the ionosphere and are being captured by the ever-increasing arrays of GNSS, such as the Global Positioning System (GPS), Globalnaya Navigazionnaya Sputnikovaya Sistema (GLONASS), and, in the future, Galileo (Occhipinti et al., 2018; Rakoto et al., 2018). The ability of tsunamis to excite internal gravity waves in the atmosphere has been recognized since the early seventies (Hines, 1972).

Long-period tsunamis transfer a small fraction of their energy to the surrounding air (Artru et al., 2005), generating perturbations that propagate both horizontally and vertically in the atmosphere in the form of internal gravity waves. These waves eventually reach the ionosphere where they can be detected by a number of different sensors. Some of these sensors are mounted on altimetry satellites and GPS-satellite systems that measure total electron content in the ionosphere or on ground-based ionospheric Doppler sounders and airglow cameras.

These technologies have successfully identified and even mapped ionospheric perturbations generated by recent tsunamis (Rolland et al., 2010; Occhipinti, 2015). However, the potential for the use of these observations in real-time tsunami forecasting remains unclear. This is because the horizontal propagation velocity of ionospheric internal gravity waves is similar to that of a propagating tsunami in the deep ocean. Since ionospheric waves have to propagate vertically to the upper layers of the atmosphere, there is an unavoidable delay between tsunami arrival and detection of its trailing internal gravity waves in the ionosphere.

In addition to tsunami-generated internal gravity waves, higher-frequency acoustic waves and acoustic gravity waves are also generated and propagated to the ionosphere by the Rayleigh waves generated at an earthquake's epicenter. These acoustic waves travel much faster than tsunami waves ($\sim$3.5 km/s) (Occhipinti, 2015) and can potentially supplement seismic information to help characterize the seismic source, thereby contributing to more accurate tsunami forecasts.

Infrasound

It has long been known that earthquakes and tsunamis emit inaudible frequencies (infrasound) that can be detected by infrasound arrays from regional to far distances, as reported by Le Pichon et al. (2002, 2005) in regard to the June 23, 2001 Arequipa, Peru earthquake; March 27, 1964 Alaska, United States earthquake; and August 18, 1959 Montana, United States earthquake. A review of the monitoring results in Diego Garcia also detected the infrasound in the 2004 Indian Ocean earthquake and tsunami. In 2005, the Diego Garcia infrasound station and stations in Palau and Madagascar also detected earthquakes in Nias and Mentawai, Indonesia, on March 28 and April 10, respectively (Garcés et al., 2005).

The idea of using infrasound as part of the global tsunami warning and mitigation system has been widely studied. Bittner et al. (2010) reported that infrasound waves affect the temperature pattern of the stratosphere to an altitude of 87 km. Infrasound waves propagate much faster than tsunami waves, making them attractive to warning centers as an independent means of confirming tsunami generation. However, additional development, testing, and evaluation of the application of infrasound to tsunami detection and forecasting are needed before this technique can be incorporated into tsunami warning center operations.

Coastal Radar

Shore-based high-frequency (HF) radar has proven to be an effective tool to measure ocean currents. The principle is based on the ability of these systems to measure the Doppler shift induced on the radar signal by the orbital velocities of water particles. This alteration of the reflectivity signal can then be inverted to obtain values of ocean current velocities in the radial direction along the line-of-sight of the radar. The use of this technology to detect approaching tsunamis was suggested by Barrick (1979) in the 1970s and has recently received new emphasis following the successful detection of propagating tsunamis in the near and far field during recent events (Hinata et al., 2011; Lipa et al., 2011; Dzvonkovskaya, 2012).

One of the advantages of tsunami detection via HF radar is its ability to provide detection over a large area as opposed to the point-based measurements of other instruments (e.g., tsunameters, GNSS, coastal sea-level stations). Current HF radar systems have a range of several hundreds of kilometers (Grilli et al., 2016) with a wide sweep angle potentially covering a substantial amount of the typical generation area of tsunamis triggered by subduction zone earthquakes.

Based on recent detection of propagating tsunamis, the role of HF radar in tsunami forecasting has been proposed primarily as an early warning tool capable of detecting an approaching tsunami. However, its ability to provide accurate and detailed tsunami height information over an earthquake rupture area still needs to be explored. For tsunami warning centers to use HF radar for this purpose, in addition to the inversion of tsunami velocities from radar signals, a second inversion is necessary to infer tsunami heights from the detected velocity field. However, the ability of current physical models to perform this inversion accurately enough to fully capture all tsunami generation processes at the source remains to be assessed.

Since the 2004 tsunami, interest in HF radar as an additional tool for tsunami detection has increased. Nevertheless, the data are not currently widely used in real-time tsunami forecast and warning operations.

Modeling and Computational Advances

Operational tsunami forecast systems have developed over the last decade following operational deployment of ocean observing systems such as tsunameters and tsunami capable coastal sea-level stations. While such forecast systems can provide forecast solutions based on rapid seismic assessment of tsunamigenic earthquakes, their strength relies on the ability to generate forecast solutions based on sea-level observations collected by tsunameters and reported in real time. It is in this mode of operation that such systems reach their highest levels of accuracy.

Today, one of the most advanced operational tsunami forecast systems is deployed in the United States at NOAA's tsunami warning centers. The current version of the United States system relies on the linear behavior of tsunamis in the deep ocean to construct an initial ocean surface deformation consistent with tsunameter observations via a linear combination of precomputed tsunami unit sources. Once appropriate initial conditions have been established, a deep-ocean propagation solution is automatically generated from the database of unit sources, while the non-linear tsunami propagation in shallow water and inundation values are computed in real time for select communities (Gica et al., 2008; Titov, 2009; Bernard and Titov, 2015).

There are two advantages to using precomputed unit sources. First, they expedite numerical computation of real-time tsunami propagation in the deep ocean by performing straightforward calculations on readily available solutions. Second, they provide the precomputed time series necessary to perform an inversion from tsunameter data. These time series are combined to fit observations during the inversion process to reconstruct the tsunami source.

There are also two main limitations to using precomputed unit sources. The most significant shortcoming is the possibility of a tsunamigenic earthquake that does not conform to either the parameters or locations in the database of precomputed unit sources (e.g., April 11, 2012 Sumatra, Indonesia; March 2, 2016 Southwest Sumatra, Indonesia; January 23, 2018 Kodiak Island, Alaska, United States). The other important limitation is the current latency of the reception of tsunameter data. Given the current density of tsunameters and the fact that most operational systems do not have the rapid detection capabilities of the DART 4G system, there is an underlying latency in the reception of sea-level observations. This slows formulation of tsunameter-based forecasts and is particularly problematic in the near field.

To improve the capabilities and address the shortcomings of the United States forecast system, state-of-the-art high-performance computing technology is being introduced. In 2019, the United States tsunami warning centers will deploy a new version of the forecast system, which is based on a version of the Method of Splitting Tsunamis (MOST) numerical model (Titov and González, 1997; De la Asunción et al., 2013; Titov et al., 2016) that takes advantage of the massive parallel architecture of modern graphics processing units (GPUs). Other tsunami warning centers in Japan and Europe are in the process of adopting similar GPU technology for tsunami forecasting (González-Vida et al., 2019).

Graphics processing units will allow the forecast system to compute up to 60 times faster than the previous version and are particularly efficient at computing problems with a relatively small computational load and minimal input/output demands but that require a fast solution turnaround (seconds to minutes), as is the case in tsunami forecasting. This means the warning centers can conduct computations in-house significantly faster than at centralized supercomputer centers, which are generally geared toward running models with less stringent turnaround requirements than the warning centers.

These enhanced computing capabilities will address the main two shortcomings associated with using precomputed unit sources by enabling the warning centers to perform real-time deep-ocean computations if a tsunamigenic earthquake does not conform to the hypocentral parameters of precomputed unit sources. In such a situation, the warning centers will be able to calculate a seismic solution (moment tensor or finite fault) or compute a new cluster of unit sources in the region where their analysis suggests the earthquake occurred and then generate a tsunameter-based inversion using the newly computed unit sources in near real time. These two processes could also be combined, generating an initial forecast based on a seismic inversion with updates provided when tsunameter data become available.

In regard to the computation of new clusters of unit sources, the system is being designed to further expedite computations of tsunameter-based inversions. Calculations of each unit source will be restricted in the newly defined cluster to a region around the epicenter that only includes data from tsunameters close to the source. Once a time series for each unit source in this region has been computed and time series from all unit sources at each of the nearby tsunameters are available, an initial ocean surface deformation can be computed and inverted and a single basin-wide tsunami propagation solution can be performed. This will eliminate the need for a full-basin computation from each unit source.

Preliminary implementation of this approach was tested using a set of newly defined unit sources up to 2 h of tsunami travel time away from the epicenter. It demonstrated that a regional solution for each unit source in the new set can be performed in approximately 10 s. These regional computations can be initiated before tsunameter data are available, further reducing the total computational time requirement.

Consequently, the introduction of new high-performance computing capabilities to the United States forecast system, in conjunction with the use of the efficient calculation strategies described above, eliminates the first of the two main shortcomings in today's forecast system, the handling of events not available in the precomputed database. In addition, it has the potential to largely reduce the problem of rapid forecast availability in the near field when used in combination with other near-field detection systems such as GNSS or DART 4G.

Other Sea-Level and Geophysical Applications

Enhancements to the coverage and real-time availability of sea level (deep ocean and coastal) and GNSS data will provide identifiable multidisciplinary benefits to many other applications. Some of these applications are noted below and in **Tables 1A,B**.

- Monitoring sea-level variations and inundation for climate research and forecasting.
- Assimilating data to support deep-ocean and coastal forecasting systems.
- Enhancing tide predictions at individual locations for navigation and maritime applications.
- Researching and operationally supporting other coastal hazard applications, such as storm surge inundation and warning.
- Researching changes in deep-ocean properties associated with climate change.
- Defining maritime boundaries more accurately.
- Monitoring tectonic plate movements.

- Conducting geodetic and land information surveys.
- Addressing other geophysical and seismic phenomena.
- Leveraging available ship-time resources for installation and maintenance.
- Improving tide measurements and datums.
- Validating satellite altimeter data.
- Improving understanding of ocean circulation.
- Supporting research and warning on related hazards such as meteotsunamis and infragravity waves.

CHALLENGES, ROADBLOCKS, AND REMAINING GAPS RELATED TO REDUCING UNCERTAINTIES

In this paper, we demonstrated that, with sufficient observations, tools exist to greatly reduce long-standing uncertainties associated with tsunami forecasts and that resolving these uncertainties would fundamentally change how emergency managers coordinate tsunami response, particularly in the near field. Today, we have neither all the required data sets nor the means to globally implement these tools. Some of the more pressing challenges are discussed below.

GNSS

We believe focusing on GNSS-derived displacement data rather than traditional seismic analysis is the best near-term strategy for rapidly reducing tsunami source uncertainties. However, the challenges are not trivial.

Coastal GNSS stations must be dense enough and configured so they can reliably represent complex seafloor deformations. The required station density does not exist, and may never exist, along many dangerous subduction zones, such as the Aleutian, Kermadec, and Sumatra trenches. In some locations with high-density coastal GNSS coverage, such as the Japan Trench, the relatively long distance between the coast and the primary tsunami source region limits the degree to which coastal displacements can accurately represent offshore deformation.

Some locations, such as the Cascadia subduction zone, New Zealand's Hikurangi fault zone, and the Chilean trench, are well suited for GNSS source estimate techniques because there are dense coastal GNSS networks in close proximity to these tsunamigenic regions. However, these are also the locations where tsunami travel times between source and coast are the shortest (Power et al., 2016). It is of utmost importance that tsunami forecast information in these regions is timely and accurate.

Seismology

Although we suggest above a focus on GNSS techniques to reduce uncertainty, the first identification of most tsunamis will continue to rely on seismology. As demonstrated in Section "Seismic Analysis" and **Appendix**, seismic detection and characterization techniques continue to develop and when combined with GNSS will be important for quickly reducing initial forecast uncertainty. Increasing the timeliness and accuracy of seismic analysis continues to present challenges and may require direct instrumentation of oceanic fault zones.

Land-Based Seismic Stations

Installation of new seismic stations and real-time access to data from more existing seismic stations are needed, particularly in low-density regions. Quicker and more accurate seismic analysis will remain important in issuing the first messages after a potentially tsunamigenic earthquake.

Tsunameters

DART 4G systems eliminate seismic noise, allowing them to be sited closer to tsunami sources to reduce detection times. However, these systems and systems like them are expensive and in some locations may provide more limited coverage than their predecessors, requiring deployment of additional systems.

Coastal Sea-Level Stations

Even if it is possible, through a combination of GNSS techniques and near-field tsunameters, to get to a point where tsunami sources can be mostly constrained within 10 min of origin, a significant level of uncertainty would remain. This is particularly true for complex inundation zones, where uncertainties can become large due to insufficient bathymetric resolution or other complicating factors such as stream outflow. Therefore, real-time coastal sea-level station data remain vital. To further support verification of the new forecasts, access to real-time data from higher densities of coastal sea-level stations is required (Intergovernmental Oceanographic Commission [IOC], 2006). In addition, it must be recognized that sea-level stations near an earthquake's epicenter may be partially or totally destroyed by an earthquake and/or tsunami as demonstrated by the 2010 Maule, Chile earthquake and tsunami (Intergovernmental Oceanographic Commission [IOC], 2010).

Cabled Observation Systems

Attaching BPRs and accelerometers to cables would provide important improvements in timeliness and accuracy needed to precisely measure tsunami sources. This is key to achieving the level of forecast certainty needed to transform global tsunami response from a series of preplanned responses based on worst-case scenarios.

Adding BPRs to commercial fiber-optic cables at large scales is likely outside the reach of the traditional tsunami warning and mitigation capability. We therefore call on the broader ocean observations community to work with us to encourage the submarine telecommunications industry to consider installing instrumentation, such as bottom pressure sensors and accelerometers, on their cables to help achieve our goals.

Observational Data Accessibility

We expect to see continued densification of seismic, deep-ocean, and coastal observing networks in the coming years. It will be of critical importance that governments ensure data from these networks are shared through standard international paths of dissemination to inform global tsunami forecast and warning applications. Equally important is that Member States realize there is a need to maintain these observing networks over the long-term to the required standards for this and other applications.

Bathymetric Data

Accurate tsunami inundation forecasts require high-resolution bathymetric data. The resolution required for tsunami inundation forecasting is approximately 10 m. Where this resolution exists, it is often for populated coastlines. In other instances, it is not available due to security reasons. The ocean observations community should work together to increase the amount of and access to high-resolution bathymetric data to support the many beneficial applications for society.[9]

Time-Distance Problem

Independent of efforts to better constrain the tsunami source, there are many sections of populated coastlines where there may never be sufficient time to produce forecasts. In these places, predetermined responses based on initial seismic analysis, rapid alerting infrastructures, and a public understanding of natural warnings may forever be required.

Other Tsunami Sources

While the primary focus of this effort has been to better constrain tsunami sources in the world's known subduction zones, we recognize that dangerous tsunamis can be created outside these zones that may require different detection and measurement strategies. Two recent events in Indonesia illustrate the need to better detect and measure all tsunamis, regardless of their source:

- On September 28, 2018, a M7.5 earthquake struck near Sulawesi. Indonesia's Agency for Meteorology, Climatology, and Geophysics (BMKG) issued tsunami alerts based on magnitude and location alone. These alerts were cancelled once the source mechanism was determined to be strike slip (such earthquakes rarely generate destructive tsunamis), tsunami heights at Marmuju were below the threshold for an alert, and the alert period had passed. There was no real-time consideration that the strike-slip event could have induced a tsunami in the relatively shallow Palu Bay over 200 km away.
- On December 22, 2018, a tsunami occurred in the Sunda Strait that was likely caused by the Anak Krakatau volcano. Since it was not a seismic event and there were no tsunameters in the vicinity, there were no indications that a tsunami had been generated until it arrived at the coast.

MOVING FORWARD: THE UNITED NATIONS DECADE OF OCEAN SCIENCE FOR SUSTAINABLE DEVELOPMENT

In February 2018, IOC/UNESCO held a workshop to review the latest developments in tsunami early warning to enhance community response. Participants discussed the remaining scientific challenges to meeting identified emergency response/mitigation needs. Following the discussion, the IOC/UNESCO Working Group on Tsunami and Other Hazards Related to Sea-level Warning and Mitigation System (TOWS-WG) debated the outcomes of the workshop (Intergovernmental Oceanographic Commission [IOC], 2018).

The consensus opinion from the workshop was that while there are, and likely always will be, large uncertainties associated with tsunami impacts in the immediate near field (i.e., within 5–10 min of generation), reliable, accurate, and more timely forecasts can be produced if we pursue improved means of constraining tsunami sources. Most notably, this would entail new ocean and coastal observation techniques and technologies or better assimilation of data from existing observation systems (Intergovernmental Oceanographic Commission [IOC], 2018). Greater forecast certainty would allow decision makers to transition from broad, preplanned responses designed for worst-case scenarios to more measured actions that better reflect the actual hazard.

This all requires improving both the science and response aspects of the global tsunami warning and mitigation system. Most of the focus of this paper has been on the scientific and observational advances needed to reduce forecast uncertainty. We recognize, however, that any step forward in this regard must be accompanied by a similar increase in community preparedness. This includes conducting training and exercises for at-risk communities, identifying evacuation routes, building vertical evacuation structures, revising regulations to accommodate specific local inundation vulnerabilities, and developing curricula that include information about local geophysical hazards.

Adding to the challenge, we strive to make these advances during a time in which we could see reduced government support for building capacity for tsunami resilience and coastal community awareness and preparedness as the memories of the devastating 2004 Indian Ocean and 2011 Tōhoku, Japan tsunamis fade. To be successful, we will need continued and enhanced engagement from governments, research institutes and universities, industry, communities, the media, and other interested parties.

Finally, we must ensure common technical standards are defined and adhered to. While technological development continues to accelerate for much of the world, many tsunami-prone countries are significantly more limited in terms of capability and capacity to implement new science applications. Therefore, measures must be put in place to ensure that tsunami warning and mitigation system development in all IOC/UNESCO Member States meets minimum standards for commonality, connectivity, and integration.

Standardization of formats is also essential to ensure tsunami warning centers can ingest and analyze data in as little as 5–10 min and to maintain uniform long-term archives. IOC/UNESCO and other relevant international agencies contributing to the global coastal and ocean observing networks must work closely together to facilitate this level of standardization among Member States.

[9] Seabed 2030 is a project to bring together and share all available bathymetric data. For more information, see https://seabed2030.gebco.net/.

For all of these reasons, the announcement of the United Nations Decade of Ocean Science for Sustainable Development could not have come at a more critical juncture in terms of providing opportunities to leverage capabilities and organizations normally outside the relatively narrow global tsunami community of interest. This initiative will provide the opportunity for industry and government entities to engage with the scientific community in ways never seen before.

Of the approaches discussed here, instrumenting commercial fiber-optic cables with BPRs and accelerometers is the most promising, but it comes with complexities and costs—costs unlikely to ever be fully offset by revenue from the scientific data stream. However, rising sea levels and the increasing risks to coastal populations are driving national governments, regional development agencies, and industry consortiums to recognize a larger business case for contributing to this once-in-a-generation opportunity. Drastically reducing the potential for great loss of life and mitigating the devastation of tsunamis resonates across a broad range of global enterprises. The global tsunami warning and mitigation community stands ready to assist governments and private sector actors in leveraging this enormous potential, whether through the Decade of Ocean Science or other similar interdisciplinary collaborations.

SUMMARY

Tsunami forecast and warning efforts have traditionally relied on seismic cueing matched to precomputed scenarios that include broad worst-case assumptions. This is particularly true for local-source tsunamis. For these potentially catastrophic events, real-time numerical tsunami models are not yet able to produce sufficiently reliable forecast information.

However, with the combination of emerging solid-earth and sea-level observation technologies, advanced analysis techniques, and innovative modeling and computational strategies, the ability to directly measure or tightly infer tsunami sources is within reach. This means it could be possible for tsunami warning centers around the world to deliver accurate tsunami arrival, height, and inundation forecasts within minutes—not hours—of generation along the majority of the world's most exposed coastlines.

With this information, emergency managers will be able to prescribe precise actions with the confidence that the forecasts will closely match observations. Communities will not have to endure hours of uncertainty before fully comprehending the threat. The vision is that emergency managers could replace their current one-size-fits-all worst-case mitigation procedures with decisive, scientifically informed responses that precisely map to the actual threat.

We are confident that driving down tsunami source and related inundation forecast uncertainties can lead to a full reconsideration of how tsunamis are mitigated globally. By connecting tsunami warning and emergency management specialists around the world with the broader ocean observations community, including governments and industry, this end state could be achieved far sooner and more effectively than it could be by the global tsunami warning and mitigation community alone.

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All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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REFERENCES

Aki, K. (1966). Generation and propagation of G waves from the Niigata earthquake of June 14, 1964: Part 2. Estimation of earthquake moment, released energy and stress-strain drop from G wave spectrum. *Bull. Earthq. Res. Inst.* 44, 73–88.

Artru, J., Lognonne, P., Occhipinti, G., Crespon, F., and Garcia, R. (2005). Tsunami detection in the ionosphere. *Space Res. Today* 163, 23–27. doi: 10.1016/S0045-8732(05)80048-8

Barnes, C. R. (2018). "Quantum leap in platforms of opportunity: Telecommunication cables," in *Challenges and Innovations in Ocean in Situ Sensors: Measuring Inner Ocean Processes and Health in the Digital Age*, eds E. Delory and J. Pearlman (Amsterdam: Elsevier Science), 33–44.

Barnes, C. R., Meldrum, D. T., and Ota, H. (2016). "Emerging subsea networks: New market opportunities for, and societal contributions from, SMART cable systems," in *Proceedings of SubOptic 2016*, Dubai.

Barrick, D. E. (1979). A coastal radar system for tsunami warning. *Remote Sens. Environ.* 8, 353–358. doi: 10.1016/0034-4257(79)90034-8

Bernard, E., and Meinig, C. (2011). "History and future of deep-ocean tsunami measurements," in *Proceedings of Oceans'11 MTS/IEEE*, Kona.

Bernard, E., and Titov, V. V. (2015). Evolution of tsunami warning systems and products. *Philos. Trans. R. Soc. Lond. A.* 373:20140371. doi: 10.1098/rsta.2014.0371

Bernard, E. N., Meinig, C., Titov, V. V., O'Neil, K., Lawson, R., Jarrott, K., et al. (2010). "Tsunami resilient communities," in *Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society*, Venice.

Bittner, M., Höppner, K., Pilger, C., and Schmidt, C. (2010). Mesopause temperature perturbations caused by infrasonic waves as a potential indicator for the detection of tsunamis and other geohazards. *Nat. Hazards Earth Syst. Sci.* 10, 1431–1442. doi: 10.5194/nhess-10-1431-2010

Butler, R., Cochran, E., Collins, J., Eblé, M., Evans, J., Favali, P., et al. (2014). *The Scientific and Societal Case for the Integration of Environmental Sensors into New Submarine Telecommunication Cables. ITU/WMO/UNESCO IOC Joint Task Force report*. Paris: UNESCO.

Church, J. A., and White, N. J. (2011). Sea-level rise from the late 19th to the early 21st century. *Surveys Geophys.* 32, 585–602. doi: 10.1007/s10712-011-9119-1

De la Asunción, M., González, J. M., and Castro, M. J. (2013). *CUDA Implementation of the Propagation Module of the MOST Model*. Seattle, WA: NOAA Center for Tsunami Research.

Dzvonkovskaya, A. (2012). "Ocean surface current measurements using HF radar during the 2011 Japan tsunami hitting Chilean coast," in *Geoscience and Remote Sensing Symposium (IGARSS), 2012 IEEE International Geoscience and Remote Sensing Symposium*, Munich, 7605–7608. doi: 10.1109/IGARSS.2012.6351867

Fine, I. V., Cherniawsky, J. Y., Thomson, R. E., Rabinovich, A. B., and Krassovski, M. V. (2015). Observations and numerical modeling of the 2012 Haida Gwaii tsunami off the coast of British Columbia. *Pure Appl. Geophys.* 172, 699–718. doi: 10.1007/s00024-014-1012-7

Fry, B., Gledhill, K. R., Kaiser, A. E., Francois-Holden, C., Power, W. L., McCurrach, S.-J., et al. (2018). Toward operational tsunami early warning in New Zealand. *Paper Presented at AGU Fall Meeting 2018*, Washington DC.

Gailler, A., Hébert, H., Schindelé, F., and Reymond, D. (2018). Coastal amplification laws for the French tsunami Warning Center: numerical modeling and fast estimate of tsunami wave heights along the French Riviera. *Pure Appl. Geophys.* 175, 1429–1444. doi: 10.1007/s00024-017-1713-9

Garcés, M., Caron, P., Hetzer, C., Pichon, A. L., Bass, H., Drob, D., et al. (2005). Deep infrasound radiated by the Sumatra earthquake and tsunami. *Eos* 86, 317–320. doi: 10.1029/2005EO350002

Geist, E. L., Titov, V. V., Arcas, D., Pollitz, F. F., and Bilek, S. L. (2007). Implications of the 26 December 2004 Sumatra–Andaman earthquake on tsunami forecast and assessment models for great subduction-zone earthquakes. *Bull. Seismol. Soc. Am.* 97, S249–S270. doi: 10.1785/0120050619

Gica, E., Spillane, M., Titov, V. V., Chamberlin, C., and Newman, J. C. (2008). *Development of the Forecast Propagation Database for NOAA's Short-term Inundation Forecast for Tsunamis (SIFT). NOAA Tech. Memo. OAR PMEL-139*. Seattle, WA: U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, Office of Oceanic and Atmospheric Research, Pacific Marine Environmental Laboratory.

González-Vida, J. M., Macías, J., Castro, M. J., Sánchez-Linares, C., de la Asunción, M., Ortega, S., et al. (2019). The Lituya Bay landslide-generated mega-tsunami. Numerical simulation and sensitivity analysis. *Nat. Hazards Earth Syst. Sci.* 19, 369–388. doi: 10.5194/nhess-19-369-2019

Gower, J. (2005). Jason1 detects the 26 December 2004 tsunami. *Eos* 86, 37–38. doi: 10.1029/2005EO040002

Grilli, S. T., Shelby, M., Grilli, A., Guerin, C.-A., Grosdidier, S., and Insua, T. (2016). "Algorithms for tsunami detection by high frequency radar: Development and case studies for tsunami impact in British Columbia, Canada," in *Proceedings of the 26th International Ocean and Polar Engineering Conference*, Rhodes, 807–814.

Guilbert, J., Vergoz, J., Schisselé, E., Roueff, A., and Cansi, Y. (2005). Use of hydroacoustic and seismic arrays to observe rupture propagation and source extent of the Mw = 9.0 Sumatra earthquake. *Geophys. Res. Lett.* 32:L15310. doi: 10.1029/2005GL022966

Hébert, H., Heinrich, P., Schindelé, F., and Piatanesi, A. (2001). Far-field simulation of tsunami propagation in the Pacific Ocean: impact on the marquesas islands (French Polynesia). *J. Geophys. Res.* 106, 9161–9177. doi: 10.1029/2000JC000552

Hébert, H., and Schindelé, F. (2015). Tsunami impact computed from offshore modeling and coastal amplification laws: insight from the 2004 indian ocean tsunami. *Pure Appl. Geophys.* 172, 3385–3407. doi: 10.1007/s00024-15-1136-4

Hébert, H., Sladen, A., and Schindelé, F. (2007). Numerical modeling of the great 2004 indian ocean tsunami: focus on the Mascarene Islands. *Bull. Seismol. Soc. Am.* 97, S208–S222. doi: 10.1785/0120050611

Hinata, H., Fujii, S., Furukawa, K., Kataoka, T., Miyata, M., Kobayashi, T., et al. (2011). Propagating tsunami wave and subsequent resonant response signals detected by HF radar in the Kii Channel, Japan. *Estuar. Coast. Shelf Sci.* 95, 268–273. doi: 10.1016/j.ecss.2011.08.009

Hines, C. O. (1972). Gravity waves in the atmosphere. *Nature* 239, 73–78.

Howe, B. M., Aucan, J., and Tilmann, F. (2016). Submarine cable systems for future societal needs. *Eos* 97, doi: 10.1029/2016EO056781

Howe, B. M., Tilmann, F., and The Joint Task Force for Smart Cables (2018). "Using submarine telecommunications cables to improve monitoring tsunamis and earthquakes: The SMART Cable concept," in *Poster presented at IOC/UNESCO Symposium: Advances in Tsunami Warning to Enhance Community Responses*, Paris.

Hughes, C. W., Williams, J., Blaker, A., Coward, A., and Stepanov, V. (2018). A window on the deep ocean: the special value of ocean bottom pressure for monitoring the large-scale, deep-ocean circulation. *Prog. Oceanogr.* 161, 19–46. doi: 10.1016/j.pocean.2018.01.011

Intergovernmental Oceanographic Commission [IOC] (2006). *Manual on Sea Level Measurement and Interpretation. Volume IV–An Update to 2006*. Paris: UNESCO.

Intergovernmental Oceanographic Commission [IOC] (2009). *Tsunami Early Warning and Mitigation System in the North Eastern Atlantic, the Mediterranean and Connected Seas, NEAMTWS, Implementation Plan*. Paris: UNESCO.

Intergovernmental Oceanographic Commission [IOC] (2010). *27 February 2010 Chile Earthquake and Tsunami Event—Post-Event Assessment of PTWS Performance*. Paris: UNESCO.

Intergovernmental Oceanographic Commission [IOC] (2016). *Manual on Sea-level Measurements and Interpretation, Volume V: Radar Gauges*. Paris: UNESCO.

Intergovernmental Oceanographic Commission [IOC] (2018). *IOC/UNESCO Symposium on Advances in Tsunami Warning to Enhance Community Responses, 12–14 February 2018, Summary Statement*. Paris: UNESCO.

Jamelot, A., and Reymond, D. (2015). New tsunami forecast tools for the French Polynesia tsunami warning system Part II: numerical modelling and tsunami height estimation. *Pure Appl. Geophys.* 172, 805–819. doi: 10.1007/s00024-014-0997-2

Kanamori, H. (1972). Mechanism of tsunami earthquakes. *Phys. Earth Planet. Inter.* 6, 246–259.

Kanazawa, T. (2013). "Japan trench earthquake and tsunami monitoring network of cable-linked 150 ocean bottom observatories and its impact to earth disaster science," in *IEEE International Underwater Technology Symposium*, Tokyo

Kaneda, Y. (2013). Real time monitoring systems and advanced simulation researches for Earthquakes/Tsunami disaster mitigation. *Paper Presented at AGU Fall Meeting 2013*, San Francisco.

Kao, H., and Shan, S.-J. (2004). The source-scanning algorithm: mapping the distribution of seismic sources in time and space. *Geophys. J. Int.* 157, 589–594. doi: 10.1111/j.1365-246X.2004.02276.x

Kao, H., Wang, K., Chen, R. Y., Wada, I., He, J., and Malone, S. D. (2008). Identifying the rupture plane of the 2001 Nisqually, Washington, earthquake. *Bull. Seismol. Soc. Am.* 98, 1546–1558. doi: 10.1785/0120070160

Le Pichon, A., Guilbert, J., Vega, A., Garcés, M., and Brachet, N. (2002). Ground-coupled air waves and diffracted infrasound from the Arequipa earthquake of June 23, 2001. *Geophys. Res. Lett.* 29, 33-1–33-4. doi: 10.1029/2002GL015052

Le Pichon, A., Herry, P., Mialle, P., Vergoz, J., Brachet, N., Garcés, M., et al. (2005). Infrasound associated with 2004–2005 large Sumatra earthquakes and tsunami. *Geophys. Res. Lett.* 32:L19802. doi: 10.1029/2005GL023893

Lipa, B., Barrick, D., Saitoh, S.-I., Ishikawa, Y., Awaji, T., Largier, J., et al. (2011). Japan tsunami current flows observed by HF radars on two continents. *Remote Sens.* 3, 1663–1679. doi: 10.3390/rs3081663

Marra, G., Clivati, C., Luckett, R., Tampellini, A., Kronjäger, J., Wright, L., et al. (2018). Ultrastable laser interferometry for earthquake detection with terrestrial and submarine cables. *Science* 361, 486–490. doi: 10.1126/science.aat4458

Meinig, C., Eblé, M. C., and Stalin, S. E. (2001). "System development and performance of the Deep-ocean Assessment and Reporting of Tsunamis (DART) system from 1997–2001," in *Proceedings of the International Tsunami Symposium 2001 (ITS 2001)*, Seattle, WA.

Melgar, D., Crowell, B. W., Geng, J., Allen, R. M., Bock, Y., Riquelme, S., et al. (2015). Earthquake magnitude calculation without saturation from the scaling of peak ground displacement. *Geophys. Res. Lett.* 42, 5197–5205. doi: 10.1002/2015GL064278

Mofjeld, H. O. (2009). "Tsunami measurements," in *Tsunamis, The Sea*, Vol. 15, eds A. Robinson and E. Bernard (Cambridge, MA: Harvard University Press), 201–235.

Mori, N., Takahashi, T., Yasuda, T., and Yanagisawa, H. (2011). Survey of 2011 Tohoku earthquake tsunami inundation and run-up. *Geophys. Res. Lett.* 38:L00G14. doi: 10.1029/2011GL049210

National Centers for Environmental Information/World Data Service [NCEI/WDS] (n.d.). *Global Historical Tsunami Database*. Avbailable at: https://www.ngdc.noaa.gov/hazard/tsu_db.shtml (accessed August, 2018).

Occhipinti, G. (2015). "The seismology of the Planet Mongo: The 2015 ionospheric seismology review," in *Subduction Dynamics: From Mantle Flow to Mega Disasters*, eds G. Morra, D. A. Yuen, S. D. King, S. M. Lee, and S. Stein (Hoboken, NJ: John Wiley and Sons), 169–182. doi: 10.1002/9781118888865

Occhipinti, G., Manta, F., Rolland, L., Watada, S., Makela, J. J., Hill, E., et al. (2018). "Ionospheric detection of tsunami earthquakes: observation, modeling and ideas for future early warning," in *Poster presented at IOC/UNESCO Symposium on Advances in Tsunami Warning to Enhance Community Responses*, Paris.

Okada, Y. (1985). Surface deformation due to shear and tensile faults in a half-space. *Bull. Seismol. Soc. Am.* 75, 1135–1154.

Percival, D. B., Arcas, D., Denbo, D. W., Eble, M. C., Gica, E., Mofjeld, H. O., et al. (2009). *Extracting Tsunami Source Parameters Via Inversion of DART Buoy Data. NOAA Tech. Memo. OAR PMEL-144*. Seattle, WA: U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, Office of Oceanic and Atmospheric Research, Pacific Marine Environmental Laboratory.

Power, W. L., Wallace, L. M., Mueller, C., Henrys, S. A., Clark, K. J., Fry, B., et al. (2016). Understanding the potential for tsunami generated by earthquakes on the southern Hikurangi subduction interface. *N. Z. J. Geol. Geophys.* 59, 70–85. doi: 10.1080/00288306.2015.1127825

Pugh, D., and Woodworth, P. (2014). *Sea-Level Science: Understanding Tides, Surges, Tsunamis and Mean Sea-Level Changes*. Cambridge: Cambridge University Press.

Rabinovich, A. B., and Eblé, M. C. (2015). Deep ocean measurements of tsunami waves. *Pure Appl. Geophys.* 172, 3281–3312. doi: 10.1007/s00024-015-1058-1

Rabinovich, A. B., Thomson, R. E., and Fine, I. V. (2013). The 2010 Chilean tsunami off the west coast of Canada and the northwest coast of the United States. *Pure Appl. Geophys.* 170, 1529–1565. doi: 10.1007/s00024-012-0541-1

Rakoto, V., Lognonné, P., Rolland, L., and Coisson, P. (2018). "Tsunami wave height estimation from GPS-derived ionospheric data," in *Poster Presented at IOC/UNESCO Symposium on Advances in Tsunami Warning to Enhance Community Responses*, Paris.

Ranasinghe, N., Rowe, C., Syracuse, E., Larmat, C., and Begnaud, M. (2017). Enhanced global seismic resolution using transoceanic SMART cables. *Seismol. Res. Lett.* 89, 77–85. doi: 10.1785/0220170068

Roch, J., Schindelé, F., Rivera, L., and Duperray, P. (2016). Very fast characterization of fault parameters through W-phase centroid inversion in the context of tsunami warning. *Pure Appl. Geophys.* 173, 3881–3893. doi: 10.1007/s00024-016-1258-3

Rolland, L. M., Occhipinti, G., Lognonne, P., and Loevenbruck, A. (2010). Ionospheric gravity waves detected offshore Hawaii after tsunamis. *Geophys. Res. Lett.* 37:L17101. doi: 10.1029/2010GL044479

Sahal, A., Roger, J., Allgeyer, S., Lemaire, B., Hébert, H., Schindelé, F., et al. (2009). The tsunami triggered by the 21 May 2003 Boumerdes-Zemmouri (Algeria) earthquake: field investigations on the French Mediterranean coast and tsunami modelling. *Nat. Hazards Earth Syst. Sci.* 9, 1823–1834. doi: 10.5194/nhess-9-1823-2009

Smith, W. H. F., Scharroo, R., Titov, V. V., Arcas, D., and Arbic, B. K. (2005). Satellite altimeters measure tsunami. *Oceanography* 18, 11–13. doi: 10.5670/oceanog.2005.62

Song, Y. T., Fukumori, I., Shum, C. K., and Yi, Y. (2012). Merging tsunamis of the 2011 Tohoku-Oki earthquake detected over the open ocean. *Geophys. Res. Lett.* 39:L05606. doi: 10.1029/2011GL050767

Suppasri, A., Shuto, N., Imamura, F., Koshimura, S., Mas, E., and Yalciner, A. C. (2012). Lessons learned from the 2011 great east japan tsunami: performance of tsunami countermeasures, coastal buildings, and tsunami evacuation in Japan. *Pure Appl. Geophys.* 170, 993–1018. doi: 10.1007/s00024-012-0511-7

Takahashi, N., Imai, I., Ishibashi, M., Sueki, K., Obayashi, R., Tanabe, T., et al. (2017). Real-time tsunami prediction system using DONET. *J. Disaster Res.* 12, 766–774.

Thomson, R. E., Fine, I. V., Rabinovich, A. B., Mihaly, S. F., Davis, E. E., Heesemann, M., et al. (2011). Observations of the 2009 Samoa tsunami by the NEPTUNE-Canada cabled observatory: test data for an operational regional tsunami forecast model. *Geophys. Res. Lett.* 38:L11701. doi: 10.1029/2011GL046728

Tilmann, F., Howe, B. M., and Butler, R. (2017). Commercial underwater cable systems could reduce disaster impact. *Eos* 98, doi: 10.1029/2017EO069575

Titov, V., and González, F. I. (1997). *Implementation and Testing of the Method of Splitting Tsunami (MOST) Model. NOAA Tech. Memo. ERL PMEL-112*. Seattle, WA: U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, Office of Oceanic and Atmospheric Research, Pacific Marine Environmental Laboratory.

Titov, V. V. (2009). "Tsunami forecasting," in *Tsunamis, The Sea*, Vol. 15, eds A. Robinson and E. Bernard (Cambridge, MA: Harvard University Press), 371–400.

Titov, V. V., Song, Y. T., Tang, L., Bernard, E. N., Bar-Sever, Y., and Wei, Y. (2016). Consistent estimates of tsunami energy show promise for improved early warning. *Pure Appl. Geophys.* 173, 3863–3880. doi: 10.1007/s00024-016-1312-1

United Nations International Strategy for Disaster Reduction [UNISDR] (2015). *Sendai Framework for Disaster Risk Reduction 2015–2030*. Geneva: UNISDR.

Vela, J., Pérez-Gómez, B., González, M., Otero, L., Olabarrieta, M., Canals, M., et al. (2014). Tsunami resonance in palma bay and harbor, majorca Island, as induced by the 2003 Western Mediterranean Earthquake. *J. Geol.* 122, 165–182. doi: 10.1086/675256

Wilcock, W. S. D., Manalang, D., Harrington, M., Cram, G., Tilley, J., Burnett, J., et al. (2017). A seafloor test of the A-0-A approach to calibrating pressure sensors for vertical geodesy. *Poster Presented at AGU Fall Meeting 2017*, New Orleans.

Williamson, A. L., and Newman, A. V. (2018). Suitability of open-ocean instrumentation for use in near-field tsunami early warning along seismically active subduction zones. *Pure Appl. Geophys.* 1–16. doi: 10.1007/s00024-018-1898-6

You, J. Y. (2010). Harnessing telecoms cables for science. *Nature* 466, 690–691. doi: 10.1038/466690a

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APPENDIX: ADVANCES IN SEISMIC ESTIMATION OF THE TSUNAMI SOURCE

Earthquake magnitude is the most basic factor in determining an earthquake's tsunamigenic potential. Since the start of instrumental seismology, seismologists have created numerous magnitude scales to serve as a proxy for earthquake size. Each scale has its own strengths and applicability.

The Richter surface wave magnitude (Ms) was long used to characterize the size of great earthquakes and infer their tsunamigenic potential. However, this scale is insufficient to resolve magnitudes that reach the mid-8 range (known as magnitude saturation), which is far below the true magnitude of the most destructive tsunamigenic earthquakes.

To address the saturation problem, Aki (1966) introduced the moment magnitude (Mw) scale in the 1960s. While other scales saturate at much lower magnitudes, the Mw scale is able to measure truly great earthquakes, such as the 1960 M9.5 Chile earthquake. In addition, it was the first scale to have a physical and geological meaning—the area of the fault times the slip across the fault times the shear modulus of the material containing the fault.

Since magnitude scales are logarithmic (i.e., with each whole number increase in magnitude, the energy release increases about 32 times), it is critical to know an earthquake's true magnitude, its Mw, in order to estimate its tsunamigenic potential. The Mw scale provided a fundamentally more useful measure of relating earthquake magnitude to tsunamigenic potential.

Below are some more recent examples of seismic analysis techniques that further refine and/or speed up tsunami source estimates.

- **Mwp:** Initial routine measurements of Mw for large earthquakes were based on analyses of seismograms from key stations but were not available until many hours or even days after an earthquake—not soon enough to be useful for tsunami warning. Recently, techniques have been developed to more quickly estimate Mw from the initial P-wave arrivals on broadband seismometers. This Mw scale, known as Mwp, can be produced just minutes after an earthquake. This is the scale now used by warning centers around the world for initial tsunami assessments.
- **W-phase CMT:** The seismic "W-phase" is a very long-period seismic signal (100–1,000 s period) that travels in Earth's mantle and arrives just after the P-wave. Within 20–30 min of earthquake origin, tsunami forecasters can now invert the seismic "W-phase" to produce a more reliable Mw estimate and identify the seismic mechanism by generating what is known as the W-phase CMT (Roch et al., 2016). Tsunami earthquakes, which are earthquakes that generate larger tsunamis than their Mw would otherwise suggest (Kanamori, 1972), generate large W-phase waves.
- **Rupture extension and location:** Fast processing of seismic and hydroacoustic array data can provide fast rupture location and extension (Guilbert et al., 2005).
- **Strong-motion centroid:** Modern strong-motion sensor networks provide a continuous measurement of large ground motions, which can be used to estimate the extent and size of a rupture. This has proven effective for earthquakes like the 2016 Kaikoura event in New Zealand (Fry et al., 2018). Traditional seismic techniques failed to characterize this earthquake as tsunamigenic due to its complicated rupture process, which involved approximately 20 faults and an onshore epicenter.
- **Back-projected energy:** Summing back-projected energy from strong-motion stations can provide estimates of the rupture extent and centroid (e.g., Kao and Shan, 2004; Kao et al., 2008). Applying back projection to the 2016 Kaikoura earthquake results in an estimated rupture that scales to M7.9 within 2 min of the earthquake's origin compared to the global M7.8 estimated 10+ min after origin. In retrospect, this magnitude and mapped rupture extent could have formed the basis of a warning within 5 min of origin. Back-projection techniques, when combined with assumptions about fault geometry, may prove useful for tsunami warning purposes, as it is possible to use the centroid estimates they produce, coupled with empirical tsunami relationships, to produce initial estimates of the likely areas of impact (Fry et al., 2018).

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Treading Water: Tools to Help US Coastal Communities Plan for Sea Level Rise Impacts

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As communities grapple with rising seas and more frequent flooding events, they need improved projections of future rising and flooding over multiple time horizons, to assist in a multitude of planning efforts. There are currently a few different tools available that communities can use to plan, including the Sea Level Report Card and products generated by a United States. Federal interagency task force on sea level rise. These tools are a start, but it is recognized that they are not necessarily enough at present to provide communities with the type of information needed to support decisions that range from seasonal to decadal in nature, generally over relatively small geographic regions. The largest need seems to come from integrated models and tools. Agencies need to work with communities to develop tools that integrate several aspects (rainfall, tides, etc.) that affect their coastal flooding problems. They also need a formalized relationship with end users that allows agency products to be responsive to the various needs of managers and decision makers. Existing boundary organizations can be leveraged to meet this need. Focusing on addressing these needs will allow agencies to create robust solutions to flood risks, leading to truly resilient communities.

Keywords: sea level, coastal processes, inundation, sea level rise, community planning

INTRODUCTION

Sea level rise is a real and present effect of climate change that is already impacting communities globally. The sea level is rising globally due to the thermal expansion and melting of land glaciers and ice sheets (Church and White, 2011), but that process is not uniform around the world. Regionally, there are other processes that can affect the rate of sea level changes (e.g., vertical land motion, ocean circulation changes, and weather events) relative to the land (known as relative sea level or RSL). The combined effects of these global and regional processes can lead to recurrent flooding events that are rapidly increasing in frequency and magnitude (Sweet and Park, 2014). These events pose a threat to coastal communities; human life and health; ecosystems and infrastructure; and require large efforts to prepare for and mitigate potential damage.

For communities to be able to adapt to and plan for the increasing frequency and severity of these events, they need access to appropriate information in a timely fashion and usable format. We discuss in this paper a number of products representing progress toward that goal. We also examine a few case studies of communities that are directly experiencing these more frequent effects of sea level changes today and look at how they are adapting.

NEEDED INFORMATION FOR COMMUNITIES TO PLAN

The most critical information communities need for planning is an understanding of the likely extent and impact of future flooding on a local scale, which emphasizes RSL rise rates – and associated extreme water levels – rather than global or regional sea level rise. RSL rise can be highly variable across relatively short distances (Boon et al., 2018) and on various timescales due to the interaction of ocean dynamics, local drivers of subsidence and tectonic activity. Therefore, increasing resilience to future flood events requires that localities have a good grasp on changing conditions at their specific location for different time horizons, and how their decision-making may alter future RSL rise rates (e.g., intense groundwater withdrawal can exacerbate local subsidence). In addition, they need to understand how rising water levels will impact infrastructure, such as roads, corrosion of underground service pipes, storm sewer networks and buildings under normal and storm conditions.

To help communities plan, a broad network of tide and land subsidence monitoring is needed to compare local conditions (short term) to long term changes at historical NOAA tide gauge stations (e.g., for the United States East Coast, **Figure 1**). These networks serve three purposes: they reduce the uncertainty inherent in extrapolating water levels to locations remote from established gauges, they capture geographically small-scale processes, and they serve as an early warning system of human-induced changes to RSL. Comparing annual trends between such newly added stations and the existing NOAA tide gauges will allow for the earlier detection of impacts of local changes due to altered hydrodynamic conditions (such as those resulting from dredging) or altered local subsidence. Where changes are due to human action (e.g., groundwater withdrawals), corrective actions can be taken to reduce RSL rise rates and increase resilience.

It is informative to know how local RSL rise has changed respective to regional and global trends over the last several decades; however, using historical data for long-term projections (e.g., end of century) may not be appropriate as future warming is likely to continue to drive an increasingly accelerated rise (e.g., Church and White, 2011; Sweet et al., 2017a) which cannot be captured in a historic record. However, sufficiently long data records of about 50 years (Boon and Mitchell, 2015), capturing important modes of variability such as annual and decadal cycles (Menéndez and Woodworth, 2010), may provide some predictive capacity important in shorter time scales, which is very important for immediate planning purposes and horizons (e.g., <30 years). This planning horizon is appropriate for many municipal-level adaptations and fits into their decision-making processes (e.g., The World Bank, 2010; Public Water Supply Utilities Climate Impact Working Group.Workshop [PWSUCIWG], 2012; Mitchell et al., 2013). For longer planning horizons (e.g., 50–100 years in the future), which are critical for risk management associated with large scale projects and projects with long lifespans, scenarios of regional sea level rise (Sweet et al., 2017b) are recommended. These projections are based on global-process models, incorporating the impact of changing climatic (over land in the ocean and atmospheric) conditions on sea level variables. They provide multiple scenarios which allow the consideration of uncertainty to be incorporated into planning efforts; leading to more robust decision making.

Moving from scenarios of projected water levels to those of projected flood impacts can be done simply, using "bathtub" mapping, where water levels are raised evenly across a digital elevation surface; but for some planning efforts, incorporating hydrodynamic models in to RSL rise mapping can provide localities with more realistic outcomes. The first type of model is useful for broad assessments of potential impacts, such as determining lifespans of roads; areas unsuitable for residential construction; and where adaptation strategies should be targeted. More detailed analyses, such as the impact of different adaptation solutions (e.g., adding tide gates, sea walls, constructing living shorelines, and elevating structures), or incorporating stormwater drainage systems into planning considerations, benefit from more dynamic models (Loftis, 2014; Wang et al., 2014). This approach requires high resolution elevation data, highly predictive models, and robust validation measures. For example, in Hampton Roads, Virginia, a street-level flooding model was compared to nearly 60,000 crowd-sourced GPS "King Tide" water levels, to validate inundation predictions (Loftis et al., 2017). The crowd-sourced data was used to improve the model fit, particularly in areas where tree cover, bridge overpasses, and culverts resulted in poor Lidar coverage. Validating hydrodynamic models with integrated observations from sensors to citizen science is useful to compare impacts of different resilience strategies, thus improving decision making (Loftis et al., 2018).

TOOLS CURRENTLY AVAILABLE

Sea Level Report Card

Sea-Level Report Cards[1] are an annually updated, web-based tool used to monitor and project changes in the sea level at 32 tide gauges along the United States coastline. Each station has three components:

(1) Projection of sea-level height to the year 2050
(2) Display of recent trends in the rates of sea-level change
(3) Explanation of processes affecting the sea level at each locality

The history and projections of each tide gauge can be used to inform management and, therefore, aid in potentially reducing

[1] http://www.vims.edu/research/products/slrc/index.php

future flood impacts by helping localities understand which forcing processes are most important to the long-term record and how their area may vary from others along their coast. Annual monitoring allows for early identification of changes in trends which might alter sea level trajectories, changing future forecasted water levels.

Federal Sea Level Rise and Coastal Flood Hazard Scenarios and Tools Interagency Task Force

A Task Force was convened in 2015 to coordinate the development and effective delivery of foundational scientific data products, information systems, and analyses to support hazard mitigation and risk management planning and decision-making in the coastal zone. These include products related to historical and future global, regional, and local SLR and associated extreme water levels, coastal flooding, wave action, coastal erosion, and shoreline changes. Its first major deliverable was the development of gridded future scenarios of relative SLR for the entire United States coastline (Sweet et al., 2017b) and the results of this work were made available via an interactive website supported by NOAA[2] and by the United States Geological Survey (USGS[3]). The scenarios adjusted upward global mean sea level (GMSL) rise amounts based on new science since from the Third National Climate Assessment (NCA) (Parris et al., 2012). The NCA's revised range of 0.3–2.5 m GMSL rise by the year 2100 spans the range of scientifically plausible future SLR across a variety of assumptions about future greenhouse gas emissions, climate system responses to those emissions, and the behavior of the Greenland and Antarctic ice sheets. The approach of Kopp et al. (2014) was leveraged to provide estimates of the probability of GMSL rise and underlying contributing processes, conditional upon greenhouse-gas emission scenarios.

These global scenarios were then used to derive regional SLR responses on a 1-degree grid covering the coastlines of the United States mainland, Alaska, Hawaii, the Caribbean, and the Pacific island territories, as well as at the locations of

[2]https://coast.noaa.gov/slr/
[3]http://arcg.is/1He0Tz

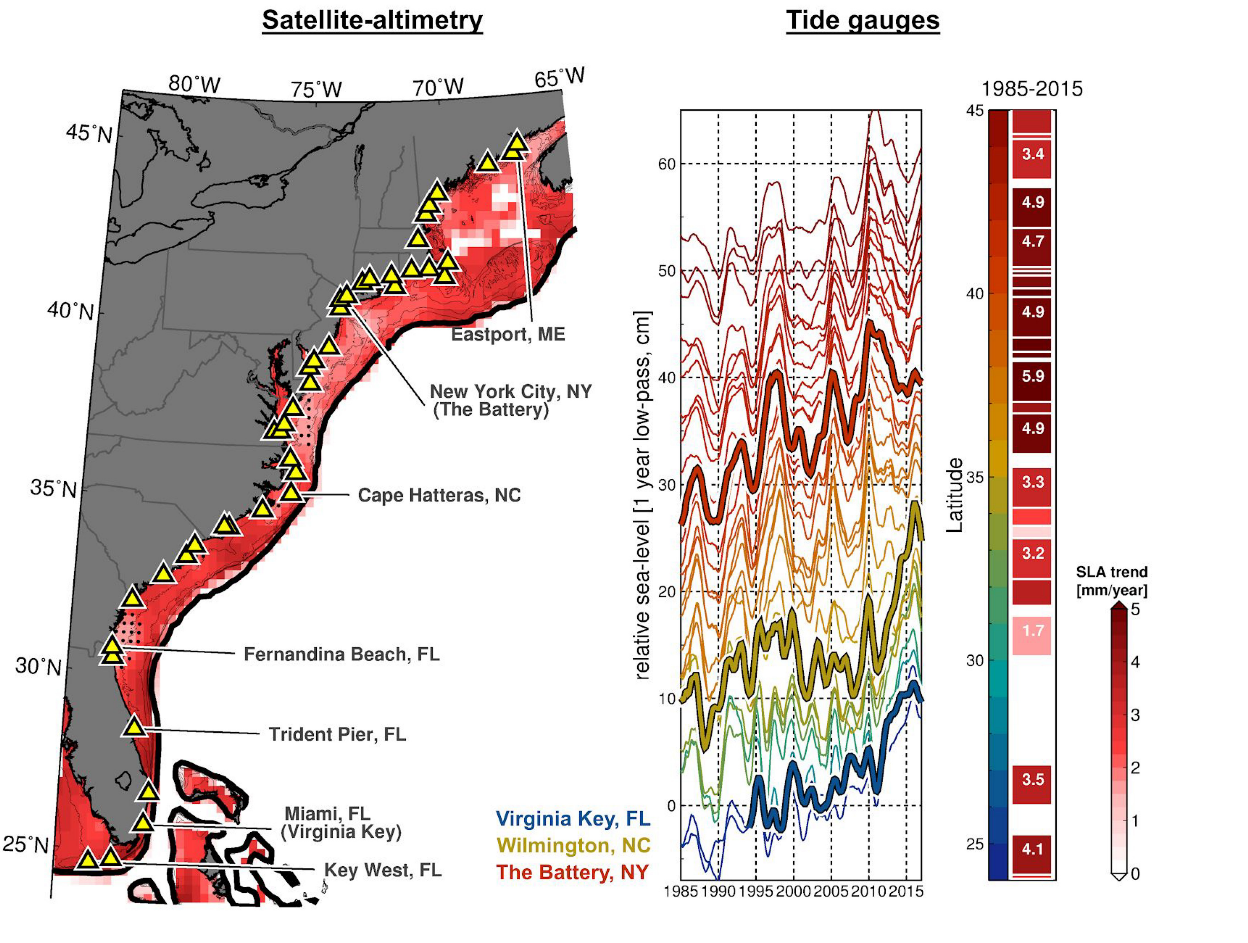

FIGURE 1 | (Left) Location of 43 tide gauges along the United States East Coast (yellow triangles) overlaid on SLR rates estimated from satellite-altimetry for the time period of 1993–2015. **(Right)** 1-year low passed time series of sea level observations at the 43 tide gauges along the United States East Coast. Time-series are offset by 1.5 cm between consecutive tide gauges for display purposes, and rates of SLR for individual tide gauges are shown to the right for the time period of 1985–2015.

individual tide gauges in between these grid cell centers. These regional scenarios were provided for six discrete GMSL rise scenarios, referred to as Low (0.3 m), Intermediate-Low (0.5 m), Intermediate (1.0 m), Intermediate-High (1.5 m), High (2.0 m), and Extreme (2.5 m). GMSL was then adjusted to account for key factors important at regional scales, including:

(1) Shifts in oceanographic variables such as circulation patterns;
(2) Changes in the Earth's gravitational field and rotation, and the flexure of the crust and upper mantle, due to melting of land-based ice; and
(3) Vertical land movement (VLM; subsidence or uplift) due to glacial isostatic adjustment, sediment compaction, groundwater and fossil fuel withdrawals, and other non-climatic factors.

Follow-on work of the Task Force used the SLR scenarios to produce future decadal estimates of high tide flood frequencies, whose impacts would be some of the first impacts of SLR and likely force initial adaptation responses (Sweet et al., 2018). A subset of the high tide flood frequency projections is available at: https://crt-climate-explorer.nemac.org/. Currently, NOAA is tracking mean sea levels relative to these scenarios to assist locations in monitoring the trajectory of local sea levels (e.g., see "Regional Scenarios" for Norfolk VA). Currently, most locations more or less track the "Low Scenario," since this scenario is basically a local/regional manifestation of the 3 mm/year global rise rate over the last couple of decades. Future projections are expected to rise somewhere between 0.5 and 1.0 m, which represent the low-end and high-end of likely rise (17th and 83rd%) under Representative Concentration Pathways (RCP) RCP4.5 and RCP8.5 conditions. This set of authoritative Federal interagency scenarios has been integrated into a variety of coastal risk management tools and capabilities deployed by individual agencies, including NOAA's Sea Level Rise Viewer (see text foot note 3), the USACE Sea Level Calculator[4], and the USGS Coastal Change Hazards Portal– as well provided online through an interactive GIS interface and associated story map[5].

We only present a couple of examples of available tools, but there are other available resources publicly available such as Sea Level Rise Viewer[6], Digital Coast[7], NASA's Sea Level Change page[8] to offer additional information for planning purposes.

CASE STUDY: UNITED STATES EAST COAST SEA LEVEL CHANGES

Some areas around the world are more vulnerable to SLR than others. Here we present one study of a vulnerable shore.

The United States East Coast includes several highly populated and low-lying urban areas that are affected by recurrent nuisance flooding events during high tides, making this region particularly vulnerable to SLR. Nuisance flooding events, which are defined by the National Weather Service as flooding between about 0.3 and 0.7 above high tide, have been increasing in frequency along the United States East Coast, and are further projected to intensify during this century (Sweet et al., 2018). Even though these events are not usually associated with damaging flooding conditions, they can cause disruption of sensitive services including urban transportation (e.g., Suarez et al., 2005), degradation of wastewater (e.g., Flood and Cahoon, 2011), and saltwater intrusion in aquifers (e.g., Sukop et al., 2018). In order to maintain resilient coastal communities, planning and adaptation efforts are already in place in many large cities including Miami (Miami-Dade County, 2010) and New York

[4] http://corpsmapu.usace.army.mil/rccinfo/slc/slcc_calc.html
[5] http://usgs.maps.arcgis.com/apps/Cascade/index.html?appid=668f6dc7014d45228c993302d3eab2f5
[6] https://coast.noaa.gov/digitalcoast/tools/slr
[7] https://coast.noaa.gov/digitalcoast/
[8] https://sealevel.nasa.gov/

TABLE 1 | Spatial and temporal scales of geophysical processes affecting water levels.

Physical Process	Spatial Scale			Temporal Scale	Magnitude (yearly)
	Global	Regional	Local		
Wind Waves (e.g., dynamical effects, run up)			X	seconds to minutes	<10 m
Tsunami		X	X	minutes to hours	<10 s of m
Storm Surge (e.g., tropical cyclones or nor'easters)		X	X	minutes to days	<15 m
Tides			X	hours	<15 m
Seasonal Cycles		X	X	months	<0.5 m
Ocean/Atmospheric Variability (e.g., ENSO response, NAO)		X	X	months to years	<0.5 m
Ocean Eddies, Planetary Waves		X	X	months to years	<0.5 m
Ocean Gyre and Over-turning Variability (e.g., Gulf Stream, AMOC)		X	X	years to decades	<0.5 m
River Discharge		X	X	years to decades	millimeters to centimeters
Land Ice Melt/Discharge	X	X	X	years to centuries	millimeters to centimeters
Thermal Expansion	X	X	X	years to centuries	millimeters to centimeters
Vertical Land Motion		X	X	minutes to centuries	millimeters to centimeters

Adapted from Sweet et al. (2017b).

City (Rosenzweig and Solecki, 2010). Sea level changes are continuously monitored along the United States East coast by 43 NOAA tide gauges (**Figure 1**). In addition, Sea-Level Report Cards[9] provide easy access to the latest updates on SLR rates and changes along this region, allowing stakeholders, coastal managers, and planners to prepare accordingly. It shows, for example, that over the past several decades, the sea level has been increasing steadily along the United States East Coast at rates ranging from 1.2 to 5.1 mm per year, with an estimated linear (quadratic) increase in sea levels by 2050 of 13 cm (24 cm) in Key West, FL, and of 29 cm (49 cm) in Norfolk, VA, United States. Which trend (linear or quadratic) best explains the current trajectory, varies from location to location. An analysis of this question can be found in Boon and Mitchell (2015). Processes linked with ocean heat uptake (steric SLR) and polar ice sheets melting are also identified as the primary drivers for long-term SLR in the region. The combined effect of various global and regional forcing mechanisms mentioned previously, can determine the mean sea level and the occurrence of flooding above a local threshold, generally during high amplitude spring tides. Ocean Dynamics, for example, even though indicated as a negligible driver for long-term SLR in the United States East Coast Sea-Level Report Card, are known for driving sizeable contributions to coastal nuisance flooding in the region over short timescales (e.g., Sweet et al., 2016; Baringer et al., 2017). **Table 1** (adapted from Sweet et al., 2017b) summarizes some of the key components causing sea level changes, along with their dominant timescale and response magnitude.

Over the past few years, recurrent flooding conditions in major cities along the United States East Coast such as New York City, Norfolk, Miami, and others (see Figure 6 of Sweet et al., 2018) have attracted particular attention from the media, and from the scientific community in search of answers for potential driving mechanisms. Some of the key mechanisms identified include those linked with natural modes of variability such as the North Atlantic Oscillation (NAO) and the El Nino Southern Oscillation (ENSO) (e.g., Sweet and Marra, 2015; Valle-Levinson et al., 2017; Sweet et al., 2018), which can modulate both mean sea level or synoptic variability (storm track tendencies). Sea level changes associated with these modes will generally result from variations in atmospheric pressure (Piecuch and Ponte, 2015), near-shore wind conditions (Woodworth et al., 2014; Thompson and Mitchum, 2014), and in large-scale ocean heat content in the region (Domingues et al., 2018). For example, it was estimated that about 50% of the observed sea level rise of ∼8 cm along the Northeast United States Coast during 2008–2010 was accounted for by low atmospheric pressure conditions observed, linked with an extremely low NAO (Piecuch and Ponte, 2015). From 2010 to 2015, increase in atmospheric pressure linked with near-neutral NAO conditions accounted for a net decline of 5–10 cm in the sea level between Cape Hatteras and Eastport. Over the same time period, a rapid increase of over 10 cm in the sea level along the Southeast United States coast was largely caused by the warming of the Florida Current, which can account for year-to-year changes in the sea level as large as 20 cm (Domingues et al., 2018).

[9]http://www.vims.edu/research/products/slrc/compare/east_coast/index.php

In addition to natural modes of variability along the United States East Coast, work toward understanding the variability from western boundary currents (Florida Current and Gulf Stream), has been studied for their impact on sea levels. The underlying geostrophic dynamics of these currents imply that the cross-stream slope of the sea level is proportional to the intensity of their flow. In general, a decline of 1 Sv (1 $Sv = 10^6\ m^3\ s^{-1}$) in their transport can cause a 0.5–5.0 cm rise in sea levels along the United States East Coast (Ezer et al., 2013; Woodworth et al., 2014; Goddard et al., 2015; Ezer, 2016; Sweet et al., 2016). This is important, as changes in the Florida Current and Gulf Stream transports can result from various forcing mechanisms (i.e., baroclinic Rossby waves originated in the east North Atlantic) that may take years to reach the United States East Coast (Domingues et al., 2016; Calafat et al., 2018). In addition, because changes in the Florida Current transport can amount to ∼10 Sv change (Schott et al., 1988; Meinen et al., 2010), it is common for widespread nuisance-flooding events along the United States East Coast to coincide with low transport (Sallenger et al., 2012; Ezer and Atkinson, 2014; Sweet et al., 2016; Baringer et al., 2017). In fact, the increased sea level rise observed in the Northeast United States coast during 2008–2010 was predominantly attributed to a weakening by 30% of the Gulf Stream and AMOC (Ezer, 2015; Goddard et al., 2015).

CONCLUSION

The information needed for robust sea level rise resilience planning requires an understanding of the drivers of sea level rise, and how those drivers are changing and interacting with local conditions. This is an active area of research, but there are still several questions that have been raised here that require further work. Having nationally available, locally tailored, toolbox solutions can help efficiently advise planning, mitigation practices, and emergency management protocols at a community scale. A number of tools have been developed over the past few years, which are being incorporated into resilience planning in some areas, but nothing yet on a national level in the United States. These types of products must be continually updated and informed by the most recent scientific understanding in order to be useful. This requires a commitment by local, state and federal decision makers to support tool maintenance. In addition, the existing tools are aimed at reducing flood impacts. Other sea level rise impacts (e.g., salinization of water supply) have received far less attention. The creation of tools to address these impacts should be considered a priority.

The two largest needs that agencies need to coordinate efforts on are integrated models and defined end user engagement processes. Integrated models would combine both multiple flood pathways (e.g., sea level rise, precipitation, and built infrastructure) into a single model. In addition, they should communicate in multiple ways to meet the needs of different stakeholders. Some stakeholders will want a single planning target (for example, the worst-case extent of flooding in 2050 under sea level rise and a major hurricane) while other stakeholders prefer flood probabilities that are more analogous to the current 100- and 500-year flood plains. Accomplishing risk communication in formats most relevant to end users leads directly to the need for a defined engagement process. Formal and responsive relationships between scientists and end users may be mediated through existing boundary organizations. Boundary organizations are already engaged in a two-way dialog with end users, both in translating science and understanding local issues. Therefore, they are perfectly placed to act as intermediaries; however, a formal structure of communication still needs to be developed. Tackling these two needs is possible within the next decade and agencies should be encouraged to take this holistic approach to addressing challenging problems such as sea level rise. Focusing on addressing these needs will allow agencies to create robust solutions to flood risks, leading to truly resilient communities.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

REFERENCES

Baringer, M. O., Smeed, D. A., Willis, J., Lankhorst, M., Hobbs, W. R., Dong, S., et al. (2017). Meridional overturning and oceanic heat transport circulation observations in the North Atlantic Ocean in "State of the climate in 2016". *Bull. Am. Meteorol. Soc.* 98, S84–S87.

Boon, J. D., and Mitchell, M. (2015). Nonlinear change in Sea Level Observed at North American Tide Stations. *J. Coast. Res.* 31, 1295–1305. doi: 10.2112/JCOASTRES-D-15-00041.1

Boon, J. D., Mitchell, M., Loftis, J. D., and Malmquist, D. L. (2018). "Anthropocene Sea Level Change: A History of Recent Trends Observed in the U.S. East, Gulf and West Coast Regions," in *Special Report in Applied Marine Science and Ocean Engineering (SRAMSOE) No. 467*, (Gloucester Point, VA: Virginia Institute of Marine Science).

Calafat, F. M., Wahl, T., Lindsten, F., Williams, J., and Frajka-Williams, E. (2018). Coherent modulation of the sea-level annual cycle in the United States by Atlantic Rossby waves. *Nat. Commun.* 9:2571. doi: 10.1038/s41467-018-04898-y

Church, J. A., and White, N. J. (2011). Sea-level rise from the late 19th to the early 21st century. *Surv. Geophys.* 32, 585–602. doi: 10.1007/s10712-011-9119-1

Domingues, R., Baringer, M., and Goni, G. (2016). Remote sources for year-to-year changes in the seasonality of the Florida current transport. *J. Geophys. Res. Oceans* 121, 7547–7559. doi: 10.1002/2016jc012070

Domingues, R., Goni, G., Baringer, M., and Volkov, G. (2018). What caused the accelerated sea level changes along the United States East Coast during 2010-2015? *Geophys. Res. Lett.* 45, 367–373.

Ezer, T. (2015). Detecting changes in the transport of the Gulf Stream and the Atlantic overturning circulation from coastal sea level data: the extreme decline in 2009–2010 and estimated variations for 1935–2012. *Glob. Planet. Chang.* 129, 23–36. doi: 10.1016/j.gloplacha.2015.03.002

Ezer, T. (2016). Can the Gulf Stream induce coherent short-term fluctuations in sea level along the US East Coast? A modeling study. *Ocean Dyn.* 66, 207–220. doi: 10.1007/s10236-016-0928-0

Ezer, T., and Atkinson, L. P. (2014). Accelerated flooding along the US East coast: on the impact of sea-level rise, tides, storms, the Gulf Stream, and the North Atlantic oscillations. *Earth's Future* 2, 362–382. doi: 10.1002/2014ef000252

Ezer, T., Atkinson, L. P., Corlett, W. B., and Blanco, J. L. (2013). Gulf Stream's induced sea level rise and variability along the US mid-Atlantic coast. *J. Geophys. Res. Oceans* 118, 685–697. doi: 10.1002/jgrc.20091

Flood, J. F., and Cahoon, L. B. (2011). Risks to coastal wastewater collection systems from sea-level rise and climate change. *J. Coast. Res.* 27, 652–660. doi: 10.2112/jcoastres-d-10-00129.1

Goddard, P. B., Yin, J., Griffies, S. M., and Zhang, S. (2015). An extreme event of sea-level rise along the Northeast coast of North America in 2009–2010. *Nat. Commun.* 6:6346. doi: 10.1038/ncomms7346

Kopp, R. E., Horton, R. M., Little, C. M., Mitrovica, J. X., Oppenheimer, M., Rasmussen, D. J., et al. (2014). Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earth's Future* 2, 383–406. doi: 10.1002/2014ef000239

Loftis, J. D. (2014). *Development of a Large-Scale Storm Surge and High-Resolution Sub-Grid Inundation Model for Coastal Flooding Applications: A Case Study during Hurricane Sandy*. Ph.D. Dissertation, College of William & Mary, Williamsburg, VA.

Loftis, J. D., Mitchell, M., Atkinson, L., Hamlington, B., Allen, T. R., Forrest, D., et al. (2018). Integrated ocean, earth and atmospheric observations in hampton roads, Virginia. *Mar. Technol. Soc. J.* 52, 68–83. doi: 10.4031/mtsj.52.2.8

Loftis, J. D., Wang, H., Forrest, D., Rhee, S., and Nguyen, C. (2017). "Emerging Flood Model Validation Frameworks for Street-Level Inundation Modeling with StormSense. *SCOPE '17*," in *Proceedings of the 2nd International Workshop on Science of Smart City Operations and Platforms Engineering*, Pittsburgh, PA.

Meinen, C. S., Baringer, M. O., and Garcia, R. F. (2010). Florida current transport variability: an analysis of annual and longer-period signals. *Deep Sea Res. Part I Oceanogr. Res. Pap.* 57, 835–846. doi: 10.1016/j.dsr.2010.04.001

Menéndez, M., and Woodworth, P. L. (2010). Changes in extreme high water levels based on a quasi-global tide-gauge data set. *J. Geophys. Res. Oceans* 115:C10011.

Miami-Dade County (2010). *Green Print – Our Design for a Sustainable Future*. Available at: http://www.miamidade.gov/greenprint/home.asp (accessed January 1, 2018).

Mitchell, M., Hershner, C., Herman, J., Schatt, D., Eggington, E., and Stiles, S. (2013). *Recurrent Flooding Study for Tidewater Virginia. Virginia Senate Document No. 3*. Gloucester Point, VA: Virginia Institute of Marine Science, College of William and Mary.

Parris, A. S., Bromirski, P., Burkett, V., Cayan, D. R., Culver, M. E., Hall, J., et al. (2012). *Global Sea Level Rise Scenarios for the United States National Climate Assessment*. Silver Spring, MD: NOAA.

Piecuch, C. G., and Ponte, R. M. (2015). Inverted barometer contributions to recent sea level changes along the northeast coast of North America. *Geophys. Res. Lett.* 42, 5918–5925. doi: 10.1002/2015gl064580

Public Water Supply Utilities Climate Impact Working Group.Workshop [PWSUCIWG] (2012). *PWSUCIWG*. Available at: http://floridawca.org/sites/default/files/documents/WorshopSummaryJan20-PWSU-CIWGfinal.pdf (accessed February 28, 2012).

Rosenzweig, C., and Solecki, W. (2010). Introduction to climate change adaptation in New York City: building a risk management response. *Ann. N.Y. Acad. Sci.* 1196, 13–18. doi: 10.1111/j.1749-6632.2009.05306.x

Sallenger, A. H. Jr., Doran, K. S., and Howd, P. A. (2012). Hotspot of accelerated sea-level rise on the Atlantic coast of North America. *Nat. Clim. Change* 2:884. doi: 10.1038/nclimate1597

Schott, F. A., Lee, T. N., and Zantopp, R. (1988). Variability of structure and transport of the Florida Current in the period range of days to seasonal. *J. Phys. Oceanogr.* 18, 1209–1230. doi: 10.1175/1520-0485(1988)018<1209:vosato>2.0.co;2

Suarez, P., Anderson, W., Mahal, V., and Lakshmanan, T. R. (2005). Impacts of flooding and climate change on urban transportation: a systemwide performance assessment of the Boston Metro Area. *Transport. Res. Part D Transport Environ.* 10, 231–244. doi: 10.1016/j.trd.2005.04.007

Sukop, M. C., Rogers, M., Guannel, G., Infanti, J. M., and Hagemann, K. (2018). High temporal resolution modeling of the impact of rain, tides, and sea level rise on water table flooding in the Arch Creek basin, Miami-Dade County Florida USA. *Sci. Total Environ.* 616, 1668–1688. doi: 10.1016/j.scitotenv.2017.10.170

Sweet, W., Dusek, G., Obeysekera, J., and Marra, J. (2018). *Patterns and Projections of High Tide Flooding Along the U.S. Coastline Using a Common Impact Threshold. NOAA Technical Report NOS CO-OPS*, Vol. 86. Silver Spring, MA: National Oceanic and Atmospheric Administration.

Sweet, W. V., Horton, R., Kopp, R. E., LeGrande, A. N., and Romanou, A. (2017a). "Sea level rise," in *Climate Science Special Report: Fourth National Climate*

Assessment, Volume I, eds D. J. Wuebbles, D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart, and T. K. Maycock (Washington, DC: U.S. Global Change Research Program).

Sweet, W. V., Kopp, R., Weaver, C. P., Obeysekera, J., Horton, R., Thieler, E., et al. (2017b). *Global and Regional Sea Level Rise Scenarios for the United States. NOAA Technical Report NOS CO-OPS*, Vol. 83. Silver Spring, MA: National Oceanic and Atmospheric Administration.

Sweet, W. V., and Marra, J. J. (2015). *2014 State of Nuisance Tidal Flooding [Supplement in NOAA NCEI, State of the CLIMATE*. Available at: http://www.ncdc.noaa.gov/sotc/national/201508 (accessed August 2015).

Sweet, W. V., Menendez, M., Genz, A., Obeysekera, J., Park, J., and Marra, J. J. (2016). In tide's way: southeast florida's september 2015 sunny-day flood. *Bull. Am. Meteorol. Soc.* 97, S25–S30.

Sweet, W. V., and Park, J. (2014). From the extreme to the mean: acceleration and tipping points of coastal inundation from sea level rise. *Earth's Future* 2, 579–600. doi: 10.1002/2014ef000272

The World Bank (2010). *Climate Risks and Adaptation in Asian Coastal Megacities: A Synthesis Report. 2010. The International Bank for Reconstruction and Development*. Washington, DC: THE WORLD BANK.

Thompson, P. R., and Mitchum, G. T. (2014). Coherent sea level variability on the North Atlantic western boundary. *J. Geophys. Res. Oceans* 119, 5676–5689. doi: 10.1002/2014JC009999

Valle-Levinson, A., Dutton, A., and Martin, J. B. (2017). Spatial and temporal variability of sea level rise hot spots over the eastern United States. *Geophys. Res. Lett.* 44, 7876–7882. doi: 10.1002/2017gl073926

Wang, H. V., Loftis, J. D., Liu, Z., Forrest, D., and Zhang, J. (2014). The storm surge and sub-grid inundation modeling in New York city during hurricane sandy. *J. Mar. Sci. Eng.* 2, 226–246. doi: 10.3390/jmse2010226

Woodworth, P. L., Maqueda, M. ÁM., Roussenov, V. M., Williams, R. G., and Hughes, C. W. (2014). Mean sea-level variability along the northeast American Atlantic coast and the roles of the wind and the overturning circulation. *J. Geophys. Res. Oceans* 119, 8916–8935. doi: 10.1002/2014jc010520

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Black Sea Observing System

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The ultimate goal of modern operational oceanography are end user oriented products with high scientific quality. Beneficiaries are the governmental services, coast and offshore based enterprises and research institutions that make use of the products generated by operational oceanography. Direct users are coastal managers, shipping, search and rescue, oil spill combat, offshore industry, ports, fishing, tourism, and recreation industry. Indirect beneficiaries, through climate forecasting based on ocean observations, are food, energy, water and medical suppliers. Availability of updated information on the actual state as well as forecast of marine environment is essential for the success and safety of maritime operations in the offshore industry. Various systems for the collection and presentation of marine data for the needs of different users have been developed and put in operation in the Black Sea. The systems are located both along the coast and in the open sea and the information they provide is used by both the maritime industry and the widest range of users. The Black Sea Monitoring and Forecasting Center in the frame of the Copernicus Marine Service is providing regular and systematic information about the physical state of the ocean, marine ecosystem and wave conditions in the Black Sea area, assimilating observations, keeping efficient operations, advanced technology and high quality modeling products. Combining and optimizing *in situ*, remote sensing, modeling and forecasting into a Black Sea observing system is a task that has to be solved, and that will allow to get a more complete and comprehensive picture of the state of the marine environment as well as to forecast future changes of physical and biogeochemical state of the Black Sea and the Black Sea ecosystem.

Keywords: Black Sea, observing system, operational oceanography, *in situ* measurements, modeling and forecasting, reanalyzes

INTRODUCTION

The Black Sea is one of the biggest semi enclosed sea basin on the Earth and have several specific features. It receives drainage from almost one-third of the continental Europe which includes 17 countries with about 160 million inhabitants. It is relatively isolated from the world ocean and has a limited exchange with the Mediterranean Sea through the Bosporus-Dardanelles Straits System.

The fresh Black Sea water and salty water of Mediterranean origin inputs generate extremely strong vertical stratification, which prevents ventilation of the deepest part of the basin causing anoxia in the deep Black Sea. Several changes in the Black Sea ecosystem have been documented including a shift from a relatively pristine phase around 70-ies to a phase of ecosystem degradation till early 90-ies (Mee, 1992; Moncheva, 1995; Zaitsev and Alexandrov, 1997; Bodeanu et al., 1998; Shiganova, 1998; Daskalov, 2002; Kideys, 2002; Yunev et al., 2002, 2005). Monitoring and understanding the role of four-dimensional circulation and thermohaline structure on the biogeochemical processes are therefore a priority among different problems that need to be addressed. In fact, majority of *in situ* observations that are commonly used for monitoring are generally based on near-shore monitoring programs or irregular oceanographic cruises that provide either non-synoptic, coarse resolution realizations of large scale processes or detailed, but time and site specific snapshots of local features. A crucial element of the Black Sea restoration and rehabilitation initiatives is the implementation of a continuous monitoring and operational observing system in the region.

The aim of this study is to provide a comprehensive review of the observing, modeling, and forecasting activities that have been carried out till now in the Black Sea, to highlight the main gaps and disadvantages of existing observing and forecasting systems and to point out future initiatives to build a sustainable, high-performance and cost effective Black Sea observing system (BSOS), tailored to the end users' needs, integrated in European ocean observing system (EOOS) and providing the necessary information for sound management and sustainable development of the Black Sea basin in line with the United Nations Decade of Ocean Science for Sustainable Development (2021–2030).

THE BLACK SEA OBSERVING AND FORECASTING SYSTEM (BSOS)

The first two Black Sea GOOS EU projects FP5 ARENA (Slabakov et al., 2006) and FP6 ASCABOS (Slabakov et al., 2007; Palazov and Valchev, 2008) fulfilled their mission set out in the Black Sea GOOS Strategic Action and Implementation Plan (Kakhaber et al., 2003) and had fostered development of operational oceanography in the region. In the frame of ARENA a detailed evaluation of the observing systems as well as identification of gaps and needs have been performed and an integrated Black Sea near-real-time (NRT) operational oceanographic forecasting system to serve end users' needs have been designed.

In the frame of FP7 PERSEUS EU project, Poulain et al. (2013) reviewed observing systems in the Southern European Seas (Mediterranean and Black Seas) and concluded that: (1) Observations are carried out episodically and, therefore, no regular records are available; (2) Observations are part of focused research efforts and their results are not available at present for sharing with a wider community.

The most important findings of these three projects and recent additional studies gives the picture of the observing systems landscape in the Black Sea. Almost all nowadays available *in situ* data from Black Sea (**Figure 1**) are provided by copernicus marine environment monitoring service (CMEMS) INS-TAC[1].

In situ Component

The number of operative coastal stations is about 85 but part of them is not equipped appropriately. While hydro-meteorological data are still collected, acquisition of biogeochemical data has been limited to an inappropriate level (Slabakov et al., 2006). POMOS – port operational marine observing system (Palazov et al., 2010) still provide real time information from coastal stations online[2].

There are three fixed platforms on the Black Sea shelf. One is an oceanographic platform situated near the Southern coast of the Crimean settlement Katsiveli (Sizov et al., 2010) and used mainly for field researches. Another two are industrial platforms: Gloria in front of the Romania coast and Galata on the Bulgarian shelf (Palazov et al., 2007). An autonomous above-water radiometer that is used for the continued assessment of the marine and atmospheric satellite products is installed on Gloria and Galata. The equipment is provided by JRC, Ispra and it is part of the international AERONET-OC system[3] (Zibordi et al., 2006).

The marine part of the system developed in the frame of MARINEGEOHAZARD project (Ranguelov et al., 2011) includes five moorings: three in Romanian and two in Bulgarian waters. Each mooring consists of surface buoy and bottom tsunami meter. On the surface buoys a set of instruments is installed including: weather station, chlorophyll sensor, CTD, oxygen, turbidity, current, electronic compass and GPS receiver. Measured variables are transmitted from the moorings to data centers using satellite communication (Palazov et al., 2016b). Two surface buoys with bottom stations were deployed in Burgas and Varna bays (Bulgarian waters) in 2015. Several meteorological and oceanographic variables are provided by these moorings (Palazov et al., 2018).

Black Sea research institutions operates research vessels used to implement monitoring programs or scientific and commercial cruises (Slabakov et al., 2006; Palazov et al., 2015). Some of them periodically collect data from fixed stations according to national monitoring programs or EU directives but there is no coordination at regional level. Experience exists also with respect to ships-of-opportunity. However, the potential of regular ferry boat lines is not fully benefited. Therefore, suitable conditions for organization of an efficient FerryBOX program are at hand.

The Black Sea pilot drifter experiment has started in 1999 and continued during the period of 2001–2003 in framework of WMO-IOC's DBCP program. Totally 49 Lagrangian meteorological drifters were deployed from October 2001 to April 2003 (Slabakov et al., 2006). Another 16 drifters were launched in 2003 and 6 additionally equipped with temperature sensor – during March–April 2004.

The Black Sea Argo story began in September 2002 when 3 profiling floats were deployed (Korotaev et al., 2006). The NICOP

[1] http://marine.copernicus.eu/

[2] http://bgodc.io-bas.bg/ma/DefaultENG.aspx

[3] https://aeronet.gsfc.nasa.gov/new_web/ocean_color.html

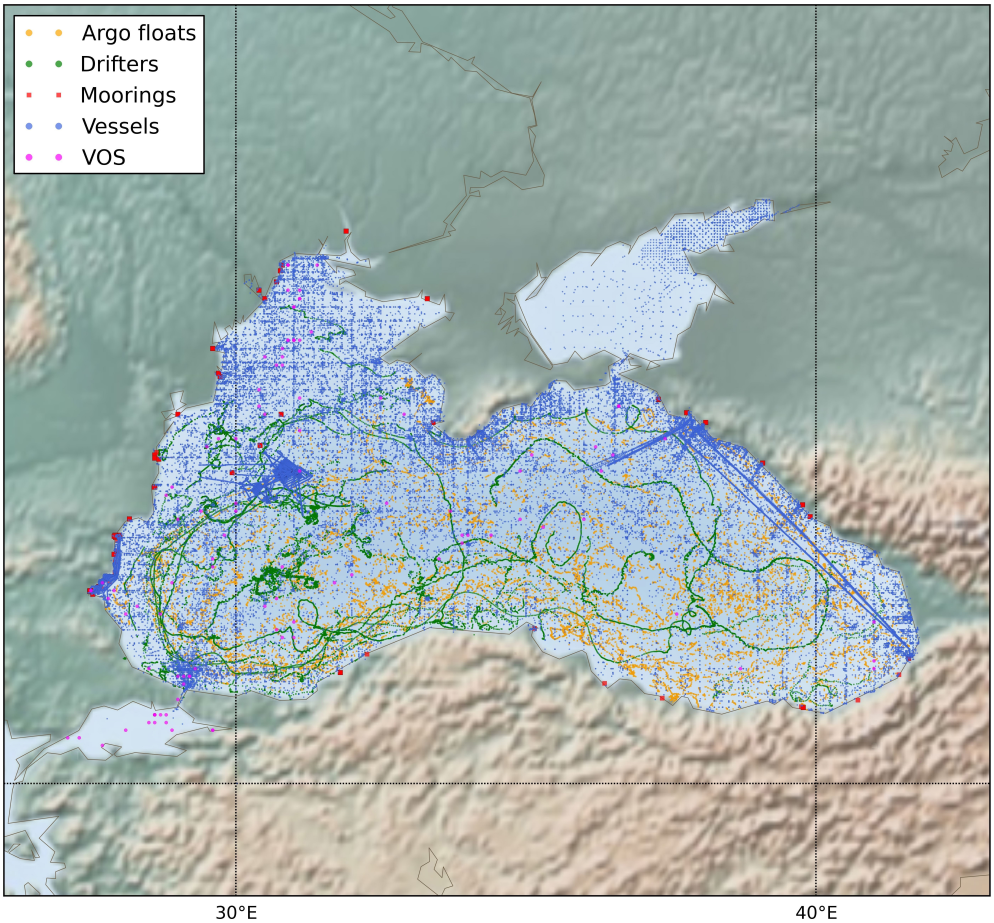

FIGURE 1 | Black Sea *in situ* data sources (1990–2018).

program led to deployment in total seven floats in the Black Sea within the period 2002–2006, but the quality of the data is not always high (Peneva et al., 2011). Other contributing programs are: HYPOX Project 2009 (Stanev et al., 2013) with two floats with DO sensors; EURO-ARGO with two floats (Peneva et al., 2011); BulArgo with four floats (Peneva et al., 2011; Palazov et al., 2012); DEKOSIM with four floats with DO sensors; MedARGO with six ARGO floats; E-AIMS with two biogeochemical floats and PERSEUS with three floats. In total 40 ARGO floats were deployed in the Black Sea (25 deployed by Bulgaria) till now (2002–2018) which provided more than 4000 CTD profiles. The Black Sea Argo experience shows that the average lifetime of the floats in Black Sea is about 36 months (Palazov et al., 2016a). The present-day number of Argo floats operating in the Black Sea of about 10, seems optimal for operational purposes (Grayek et al., 2015). According to the recommendations given by Poulain et al. (2009), the minimum population of five active floats is required for monitoring of the Black Sea.

Remote Sensing

Physical properties of the ocean such as sea surface temperature and slope, wave height and surface winds are currently measured globally at high resolution using satellites, providing information on the physical state of the ocean and reliable inputs to ocean circulation models. Similarly, ocean color measurements of phytoplankton pigment concentration are now used to monitor the marine ecosystem as well as to validate marine bio-geochemical models. In particular, the most used are the remotely sensed measurements of sea surface temperature (SST), altimeter data (sea surface height, SSH), ocean color (OC) measurements (chlorophyll, water transparency, remote sensing reflectance) and sea surface salinity (SSS). The most important source of satellite data is the ESA Sentinel program.

Modeling and Forecasting

While the observing systems limit us to data on the past and present of the marine environment, modeling and forecasting allow us to have data on the future state of the sea. Thus models and forecasts become part of the observing system in wider context.

ARENA, 2003–2006

One of the major goal of ARENA project was to develop pilot nowcasting/forecasting system in the basin

(Slabakov et al., 2006). The core basin-wide circulation model is the MHI NASU one that assimilates remote sensing data for the near-real time nowcasting and forecasting of three-dimensional fields of temperature, salinity and current (Dorofeev and Korotaev, 2004). The ecosystem module is based on the one-dimensional bio-geochemical nitrogen cycle model (Oguz et al., 1999, 2001). Four regional models are nested to the basin-scale circulation model.

ECOOP, 2007–2010

The Black Sea coastal nowcasting and forecasting system (Kubryakov et al., 2012) was built within the framework of EU FP6 ECOOP project for five regions: the south-western basin along the coasts of Bulgaria and Turkey, the northwestern shelf along the Romanian and Ukrainian coasts, coastal zone around of the Crimea peninsula, the northeastern Russian coastal zone and the coastal zone of Georgia. The system operates in the real-time mode during the ECOOP project and afterward. Ecosystem model operates in the off-line mode near the Crimea coast.

MyOcean, 2009–2015

MyOcean's objective was to set up (definition, design, development and validation) an integrated Pan-European capability for ocean monitoring and forecasting, using nationally available skills and resources. The Black Sea coastal forecasting system forms a basis for the operations of the Black Sea Marine Forecasting Center build in the frame of the EU MyOcean project. The center provides the Basin-scale analysis and forecast product of the Black Sea circulation and stratification (temperature, salinity, currents, and sea level) as well as phytoplankton and nitrate concentration.

CMEMS BS-MFC, 2016–2021

Since 2016, the Black Sea monitoring and forecasting centre (BS-MFC) in the frame of CMEMS is providing regular and systematic information about the physical state of the ocean, marine ecosystem and wave conditions in the Black Sea area, keeping efficient operations, advanced technology and high quality modeling products (Palazov et al., 2017, 2018; Peneva et al., 2017; Ciliberti et al., 2018). To guarantee high quality products based on the scientific state-of-the-art modeling frameworks and high operational reliability and robustness, the BS-MFC implements three Production Units, one for Physics, one for Biogeochemistry and one for Waves, fully connected to the CMEMS Dissemination Unit, in charge for products delivery, and supported by a Local Service Desk for supporting producers and CMEMS users on daily operations. The BS-MFC provides near real time and multiyear products for characterizing the Black Sea ocean dynamics, biogeochemical processes and wave conditions (**Table 1**). The modeling framework is built upon the state-of-the-art numerical models (NEMO ocean model for Physics, BAMHBI – BiogeochemicAl Model for Hypoixc and Benthic Influenced Areas (Grégoire et al., 2008; Grégoire and Soetaert, 2011; Capet et al., 2016) online coupled to GHER3D for Biogeochemistry (Grégoire et al., 2004, 2008; Vandenbulcke et al., 2010; Capet et al., 2016) and WAM – third generation spectral model for Waves (Wamdi Group, 1988; Komen et al., 1994; Staneva et al., 2015) and data assimilation techniques, able to carry on the impact and the evolution of the future observing network (Staneva et al., 2016; Wiese et al., 2018; Behrens et al., 2019). The BS-MFC provides information on essential ocean variables such as temperature, salinity, sea surface height, currents, concentration of chlorophyll, nutrients, dissolved oxygen, phytoplankton carbon biomass, and 2D field of vertically integrated net primary production and bottom oxygen concentration (for the shelf), significant wave height, the mean wave period, the mean wave direction, the Stokes drift, the wind wave, the primary swell wave and the secondary swell wave. Furthermore, the BS-MFC contributes to the annual Ocean State Report (von Schuckmann et al., 2018), which is becoming the European scientific reference aiming to provide a comprehensive and state-of-the art assessment of the current state, natural variations, and changes in the global ocean and European regional seas, including the Black Sea. It is meant to act as a reference document for the ocean scientific community, business community, policy and decision-makers as well as the general public. Finally, BS-MFC contributes to the delivering of Ocean Monitoring Indicators (OMI, 2018).

BSOS CONNECTIONS WITH OTHER OBSERVING SYSTEMS/PROGRAMS

Copernicus

Nowadays Copernicus EU program has a valuable contribution to the BSOS. CMEMS BS-MFC is providing both basin scale NRT and multiyear products while BSOS is providing *in situ* data for the need of INS-TAC of CMEMS.

EMODNet

Black Sea is presented in all seven EMODNet thematic portals. Black Sea checkpoint is a wide monitoring system assessment activity aiming to support the sustainable Blue Growth at the scale of the European Black Sea by clarifying the observation landscape, evaluating the fitness for use of current observations and data assembly programs toward targeted applications (challenges) and prioritizing the needs to optimize monitoring systems in terms of availability, operational reliability, efficiency, time consistency, space consistency, etc.

WHY DO WE NEED A LONG-TERM BLACK SEA OBSERVING SYSTEM?

The review of the existing Black Sea observing systems made above shows a number of shortcomings and gaps in terms of observed parameters, spatial and temporal distribution of data (Lyubartse et al., 2018), non-harmonization of individual systems, lack of standardization, lack of regular data exchange and insufficient regional cooperation. Reference *in situ* data are also mandatory for regional satellite products validation and calibration. To improve near real time system skill scores and multiyear products quality of Physics, Biogeochemistry and Wave systems, a robust observing network is fundamental. Currently, the lack of independent data represents a limit for hydrodynamic core model validation, especially in shallow areas where quality checked and consistent near real time data is insufficient. The lack of data applies as well for *in situ* wave measurements: mooring buoy stations distributed along the coastal area are extremely insufficient and not continuous in time. To drive the new scientific challenges for the development of the Black Sea operational systems, it is necessary to define also new technological opportunities for improving both satellite and *in situ* infrastructures, able to support the R&D activities such as the modeling and assimilation capabilities, validation and verification of modeling and satellite products, real time monitoring, estimation of quality of physical variables (e.g., mixed layer depth, stratification, cold intermediate layer content). The future plans for improving the quality of modeling products and their accuracy in the Black Sea require a considerable investment in empowering the observing system network toward the coastal areas as well as a reliable modeling framework able to account new observations and evaluate the impact on error characterization.

Scientific Questions

The following subset of scientific questions outlines the essential motivation for the Black Sea observing system: (1) What long-term trends can be observed in the physical and biogeochemical state of the Black Sea? (2) What is the current state of the Black Sea and could one identify regime shifts? (3) What is the Black Sea system variability ranging from mesoscale, seasonal, interannual to decadal time scales? How does the sea respond to the global atmospheric forcing and how the climate influence propagates from surface to deep layers? (4) Which mechanisms control the vertical water mass transformation and the position of the thermocline, halocline and oxycline? (5) What is the impact of the Bosporus and Kerch Strait flows on the physical and biogeochemical processes? (6) What is the role of the Black Sea in the regional climate change? (7) What are the level of anthropogenic stressors in terms of nutrient loads, atmosphere heating, deoxygenation, acidification etc., which still conserve the ecosystem health?

Society Challenges

The analysis of information received during the extensive inquiry among all potential end users (Slabakov et al., 2006) reveals variety of data and information needs encompassing physical, chemical, and biological observation. Several classes of users of BSOS data and products are specified such as: shipping, offshore oil and gas industry, ports, coastal tourism and recreation, fishing and aquaculture, coastal managers, civil protection, oil spills combat, search and rescue, environmental protection etc. The common requirement concerns development of forecasting system providing accurate real-time or near-real time information assisting decision making and environmental management.

Fill Gaps and Needs

Some of these issues of concern and gaps are the following:

- Lack of real time oceanographic data;
- Poor geographical coverage;
- Lack of modern instruments and sensors;
- Lack or sparse monitoring of biogeochemical parameters, waves and currents;
- Need for homogenization of data management.

TABLE 1 | CMEMS BS-MFC operational products.

	BS-PHY	BS-BIO	BS-WAV
Variables	3D temperature, salinity, currents, sea surface height, bottom temperature, mixed layer depth	3D concentration of chlorophyll, nutrients (nitrate and phosphate), dissolved oxygen, phytoplankton carbon biomass, and 2D field of vertically integrated net primary production and bottom oxygen concentration (for the shelf)	Most relevant wave parameters and variables, such as the 2D significant wave height, the mean wave period, the mean wave direction, the Stokes drift, the wind wave, the primary swell wave and the secondary swell wave.
Temporal resolution	NRT: Daily/Hourly means	NRT: Daily means	NRT: Hourly instantaneous
	MYP: Monthly/Daily means	MYP: Monthly/Daily means	MYP: Hourly instantaneous
Available time series	NRT: from 2016-ongoing	NRT: from 2016-ongoing	NRT: from 2016-ongoing
	MYP: January 1992 – December 2017	MYP: January 1992 – December 2017	MYP: January 2002 – December 2017
Product name in CMEMS Catalog	NRT: PHYS_007_001	NRT: BIO_007_008	NRT: WAV_007_003
	MYP: PHYS_007_004	MYP: BIO_007_005	MYP: WAV_007_006
Description of the model setup	NEMO, 1/27°×1/36°, 31 levels, TKE vertical mixing scheme ECMWF atmospheric forcing Assimilation of ARGO T,S profiles, SLA and SST using 3DVAR scheme Main rivers as climatological means, the Bosporus as SBC	BAMHBI system online coupled with GHER3D, 1/22° res., 31 levels Assimilation of ARGO oxygen data using SEEK filter ECMWF atmospheric forcing Major rivers (and the Bosporus as an open sea boundary condition)	Black Sea Wave model based on WAM, 1/27° × 1/36° wave spectra discretization: 30 frequency and 24 directional bins ECMWF atmospheric forcing Assimilation of SWH from satellite using optimal interpolation

NRT, near real-time; MYP, multi year product.

RECOMMENDATIONS FOR A SUSTAINED BSOS

As a potentially integrated part of EOOS, BSOS should be a system of monitoring and forecasting systems, providing essential ocean variables (EOV) from days to decades and from shore to the high seas, responding to the needs of science and society, contributing to the quality of life and the well-being of citizens, supports the sustainable use of Black Sea resource and contributes to the challenges of climate change (Tintoré et al., 2015b). It should be built on well-defined and generally accepted principles, in particular related to the issues of multi-platform observing, technological development, physical and biogeochemical data and connectivity, sustainability, free availability of data and support for the next generation of ocean scientists. The principles as outlined in the Strategy vision document (Tintoré et al., 2015a) should guide the development, decision making and interaction with BSOS partners, users and other collaborating institutions.

Existing observing systems should be upgraded with new sensors and technologies as a focus should be on biosensors. Antifouling technologies should be implemented to secure long term observations using optical sensors. Application of wave riders to provide data needed for assimilation in the wave models and verification of the wave forecasts is considered as important. HF radars as an effective instrument for coastal researches are strongly recommended. Integration of existing observing systems delivering *in situ* data, remote sensing data, modeling and forecasting toward delivering products for science, marine industry and society is an approach without alternative.

There must be an effort during the upcoming period toward an effective basin scale and EU cooperation and coordination between agencies and research institutes in order to establish a more homogeneous management of the observing systems, and they to begin to apply the same best management practice, uniform quality standards and common vocabularies. Each operator must be encouraged to submit all necessary information in pan European directories and databases, keep track of changes and update regularly. Data management recommendations must be circulated to operators and validation-calibration procedures must be established in a more comprehensive way. Support new buoy deployments emphasizing in offshore locations of important transitional areas where timeseries will boost research studies and operational work. Emphasis must also be given in integrating biochemical sensors as time series moorings are at present the only method/technology to provide a complete long term suite of biogeochemical variables, such as chlorophyll, oxygen, CO_2, and nutrients. These data are essential for validation and assessment purposes. Operators must keep track of new sensor technologies and propose new fields of research and monitoring such as environmental studies, marine litter, marine noise etc.

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All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication. In particular AP as the lead author, coordinated the drafting and wrote the major part of the review. SC is the lead author of modeling and forecasting activities in particular CMEMS BS-MFC part and wrote this part with the contributions of EP, MG, JS, BLD, SM, NP, LV, AB, LL, GC, RL, SC, FP, LS, NV, and PA. VM and VS contributed to introduction, *in situ* and remote sensing components description. EP and NP contributed to analysis of scientific questions, gaps and needs. EP, JS, MG, VM and VS helped to improve the manuscript during the review process. AP has taken primary responsibility for communication with the journal and editorial office during the submission process, throughout peer review and during publication.

REFERENCES

Behrens, A., Staneva, J., and Geyer, G. (2019). Verification of a high resolution operational wave model in the data sparse Black Sea. *J. Operat. Oceanogr.* (in press).

Bodeanu, N., Moncheva, S., Ruta, G., and Popa, L. (1998). Long-term evolution of the algal blooms in Romanian and Bulgarian Black Sea waters. *Cercetari Mar.* 31, 37–55.

Capet, A., Meysman, F. J. R., Akoumianaki, I., and Soetaert, K. (2016). Integrating sediment biogeochemistry into 3D oceanic models: a study of benthic-pelagic coupling in the Black Sea. *Ocean Model.* 101, 83–100. doi: 10.1016/j.ocemod.2016.03.006

Ciliberti, S., Atanas, P., Marilaure, G., Joanna, S., Elisaveta, P., and Benedicte, L. D. (2018). "The copernicus marine service for the Black Sea: products for user needs, modelling challenges and future perspectives," in *Proceedings of the European Ocean Observing System Conference EOOS*, (Brussels).

Daskalov, G. M. (2002). Overfishing drives a trophic cascade in the Black Sea. *Mar. Ecol. Prog. Ser.* 225, 53–63. doi: 10.3354/meps225053

Dorofeev, V., and Korotaev, G. (2004). Assimilation of the satellite altimetry data in the eddy-resolving model of the Black Sea circulation. *Mar. Hydrophys. J.* 1, 52–68.

Grayek, S., Emil Stanev, V., and Johannes, S. S. (2015). Assessment of the Black Sea observing system. A focus on 2005-2012 Argo campaigns. *Ocean Dyn.* 65, 1665–1684. doi: 10.1007/s10236-015-0889-8

Grégoire, M., Raick, C., and Soetaert, K. (2008). Numerical modelling of the central black sea ecosystem functioning during the eutrophication phase. *Prog. Oceanogr.* 76, 286–333. doi: 10.1016/j.pocean.2008.01.002

Grégoire, M., and Soetaert, K. (2011). Carbon, nitrogen, oxygen and sulfide budgets in the Black Sea: a biogeochemical model of the whole water column coupling the oxic and anoxic parts. *Ecol. Model.* 15, 2287–2301. doi: 10.1016/j.ecolmodel.2010.06.007

Grégoire, M., Soetaert, K., Nezlin, N. P., and Kostianoy, A. G. (2004). Modellingthe nitrogen cycling and plankton productivity in the Black Sea using a three-dimensional interdisciplinary model. *J. Geophys. Res. Oceans* 109:C05007. doi: 10.1029/2001JC001014

Kakhaber, B., Cordoneanu, E., Gennady, K., and Kubryakov, A. I. (2003). *Black Sea GOOS Strategic Action and Implementation Plan. Goos Report, 133 (IOC/INF-1176)*. Paris: UNESCO.

Kideys, A. (2002). "The comb jelly Mneniopsis leidyi in the Black Sea," in *Invasive Aquatic Species of Europe: Distribution, Impacts and Management*, ed. E.

Leppäkoski (Dordrecht: Kluwer Academic), 56–61. doi: 10.1007/978-94-015-9956-6_6

Komen, G. J., Cavaleri, L., and Donelan, M. (1994). *Dynamics and Modelling of Ocean Waves*. Cambridge: Cambridge university press.

Korotaev, G., Oguz, T., and Riser, S. (2006). Intermediate and deep currents of the Black Sea obtained from autonomous profiling floats. *Deep Sea Res. II* 53, 1901–1910. doi: 10.1016/j.dsr2.2006.04.017

Kubryakov, A. I., Korotaev, G. K., Dorofeev, V. L., Ratner, Y. B., Palazov, A., Valchev, N., et al. (2012). Black Sea coastal forecasting system. *Ocean Sci.* 8, 183–196. doi: 10.5194/os-8-183-2012

Lyubartse, V., Nadia, P., Atanas, P., Violeta, S., Luminita, B., Frederique, B., et al. (2018). *Black Sea Checkpoint Second Data Adequacy Report*. Available at: http://emodnet-blacksea.eu/wp-content/uploads/2018/04/D15.4_DAR2_v7_FINAL.pdf (accessed October 30, 2018).

Mee, L. D. (1992). The Black Sea in Crisis: a need for concerted international action. *Ambio* 21, 278–286.

Moncheva, S. (1995). "Phytoplankton under the influence of eutrophication - peculiarities and ecological significance," in *Proceedings of the Symposium on "Ecological Problems and Economical Prospects of the Black sea"*, (Istanbul: Black Sea Foundation), 271–279.

Oguz, T., Ducklow, H., Malanotte-Rizzoli, P., Murray, J. W., Vedernikov, V., and Unluata, U. (1999). A physical-biochemical model of plankton productivity and nitrogen cycling in the Black Sea. *Deep Sea Res., I* 46, 597–636. doi: 10.1016/s0967-0637(98)00074-0

Oguz, T., Murray, J. W., and Callahan, A. (2001). Simulation of suboxic-anoxic interface zone structure in the Black Sea. *Deep Sea Res. I* 48, 761–787. doi: 10.1016/s0967-0637(00)00054-6

OMI (2018). *Ocean Monitoring Indicators*. Available at: http://marine.copernicus.eu/science-learning/ocean-monitoring-indicators/ (accessed October 30, 2018).

Palazov, A., Giovanni, C., Stefania, A. C., Marilaure, G., Joanna, S., and Elisaveta, P. (2017). The Black Sea monitoring and forecasting center (bs-mfc) in the framework of the copernicus marine service. *Geophys. Res. Abstr.* 19, EGU2017–EGU15637.

Palazov, A., Violeta, S., and Veselka, M. (2018). "New sources of in-situ marine data to support EC marine strategy framework directive implementation in the black sea, in operational oceanography serving sustainable marine development," in *Proceedings of the 8th EuroGOOS International Conference*. eds E. Buch, V. Fernández, D. Eparkhina, P. Gorringe, and G. Nolan (Bergen: EuroGOOS), 89–96.

Palazov, A., Slabakov, H., and Stefanov, A. (2007). "Galata platform weather and seastate observing system," in *Marine Industry, Ocean Engineering and Coastal Resources*. eds G. Soares and P. N. Kolev (London: Taylor & Francis Group), 755–760.

Palazov, A., Slabakova, V., Peneva, E., Staefanov, A., Marinova, V., Milanova, M., et al. (2012). "BULARGO activities in the Black Sea," in *Proceedings of the TU-Varna International Jubilee Congress*. (Varna), 110–115.

Palazov, A., Slabakova, V., Peneva, E., and Stanev, E. (2016a). "Black Sea Argo history, current status and prospect, operational oceanography for sustainable blue growth," in *Proceedings of the 7th EuroGOOS International Conference*, eds E. Buch, Y. Antoniou, D. Eparkhina, and G. Nolan (Lisbon: EuroGOOS AISBL), 519–526.

Palazov, A., Stefanov, A., Marinova, V., and Slabakova, V. (2016b). "Operational oceanography products and services for maritime industry, operational oceanography for sustainable blue growth," in *Proceedings of the 7th EuroGOOS International Conference*. eds E. Buch, Y. Antoniou, D. Eparkhina, and G. Nolan (Brussels: EuroGOOS AISBL), 145–156.

Palazov, A., Stefanov, A., Marinova, V., and Slabakova, V. (2010). "Operational marine observing system to support safety port navigation", in *Proceedings of the Tenth International Conference on Marine Sciences and Technologies "Black Sea 2010"* (Varna: Bulgaria), 308–312.

Palazov, A., Stanchev, H., and Valcheva, N. (2015). "Bulgarian Black Sea Monitoring Programme 2015," in *Proceedings of 12th International Conference on the Mediterranean Coastal Environment - MEDCOAST*. (Varna).

Palazov, A., and Valchev, N. (2008). "Advance in the Black Sea regional efforts to build and sustain the operational status of oceanographic services," in *Proceedings of EuroGOOS Conference 2008, Coastal to Global Operational Oceanography: Achievements and Challenges*, (Exeter), 380–387.

Peneva, E., Emil, S., and Atanas, P. (2017). "The new copernicus black sea monitoring and forecasting centre: towards black sea operational oceanography," in *Proceedings of the 3rd National Congress on Physical Sciences*. (Sofia).

Peneva, E., Stanev, E., Palazov, A., Korchev, G., Slabakova, V., Milanova, M., et al. (2011). "BULARGO national research infrastructure: the present state and perspectives for the Argo data in the Black Sea," in *Proceedings of the 10th International Conference on Marine Sciences and Technologies "Black Sea 2010"*. (Bulgaria), 318–323.

Poulain, P. M., Solari, M., Notarstefano, G., and Rupolo, V. (2009). *Assessment of the Argo Sampling in the Mediterranean and Black Seas (part II). OGS Technical Report OGS 2009/139*. OGA: Trieste: 1–23.

Poulain, P.-M., Tintoré, J., Heslop, E., Manzella, G., Schroeder, K., Kassis, D., et al. (2013). *Review of Ocean Observing Systems in the SES and Recommendations on Upgrades to Serve PERSEUS Needs*. New York, NY: *PERSEUS*.

Ranguelov, B., Radichev, R., Dimovsky, S., Oaie, G., Dimitriu, R., Diaconescu, M., et al. (2011). MARINEGEOHAZARDS project – key core elements of the early warning sysyem in the Black Sea. *Geol. Geophys.* 54, 177–182.

Shiganova, T. A. (1998). Invasion of the Black Sea by the ctenophore Mnemiopsisleidyi and recent changes in pelagic community structure. *Fish. Oceanogr.* 7, 305–310. doi: 10.1046/j.1365-2419.1998.00080.x

Sizov, A. A., Kuznetsov, A. C., Polonski, A. B., and Spichak, N. I. (2010). "History of the creation and operation of the stationary oceanographic platform in Katsiveli (on the 30th anniversary)." in *Ecological Safety of the Coastal and Shelf Zones and the Integrated use of Shelf Resources*. Vol. 21, (Russian), 69–73.

Slabakov, H., Palazov, A., Besiktepe, S., Korotaev, G., Nikolaev, S., and Bilashvili, K. (2006). "Recent advance in the black sea operational oceanography within the arena project," in *Proceedings of the 1st Biannual Scientific Conference "Black Sea Ecosystem 2005 and Beyond"*. (Istanbul), 1229–1244.

Slabakov, H., Palazov, A., and Valchev, N. (2007). ASCABOS - a new capacity building programme supporting oceanographic services in the Black Sea. *Rapp. Comm. Int. Mer Médit.* 38:199.

Stanev, E., He, Y., Grayek, S., and Boetius, A. (2013). Oxygen dynamics in the Black Sea as seen by Argo profiling floats. *Geophys. Res. Lett.* 40, 3085–3090. doi: 10.1002/grl.50606

Staneva, J., Behrens, A., and Wahle, K. (2015). Wave modelling for the coastal-ocean predicting system. *J. Phys.* 633, 233–254.

Staneva, J., Wahle, K., Koch, W., Behrens, A., Fenoglio-Marc, L., and Stanev, E. (2016). Coastal flooding: impact of waves on storm surge during extremes. *Nat. Hazards Earth Syst. Sci.* 16, 2373–2389. doi: 10.5194/nhess-16-2373-2016S

Tintoré, J., Leonidas, P., and Heslop, E. (2015a). "Strategy for an integrated ocean observing system in the mediterranean and Black Seas," in *Proceedings of the Kostas Nittis Scientific and Strategic Workshop*. (Athens).

Tintoré, J., Perivoliotis, L., Heslop, E. E., Poulain, P.-M., Crise, A., and Mortier, L. (2015b). *Recommendations for European long term sustained observations in the SES*. New York, NY: PERSEUS Project.

Vandenbulcke, L., Beckers, J. M., Capet, A., Grégoire, M., and Besiktepe, S. (2010). Onboard Implementation of the GHER M odel for the Black Sea, with SST and CTD Data Assimilation. *J. Operat. Oceanogr.* 3, 47–54. doi: 10.1080/1755876X.2010.11020117

von Schuckmann, K., Pierre-Yves, L. T., Neville, S., Ananda, P., Pierre, B., Katja, F., et al. (2018). Copernicus marine service ocean state report. *J. Operat. Oceanogr.* 11(Suppl. 1), S1–S142. doi: 10.1080/1755876X.2018.1489208

Wamdi Group. (1988). The WAM model – a third generation ocean wave prediction model. *J. Phys. Oceanogr.* 18, 1775–1810. doi: 10.1175/1520-0485(1988)018<1775:twmtgo>2.0.co;2

Wiese, A., Staneva, J., Schultz-Stellenfleth, J., Behrens, A., Fenoglio-Marc, L., and Bidlot, J. R. (2018). Synergy between satellite observations and model simulations during extreme events. *Ocean Sci.* 14, 1503–1521.

Yunev, O., Moncheva, S., and Carstensen, J. (2005). Long-term variability of vertical chlorophyll a and nitrate profiles in the open Black Sea: eutrophication and climate change. *Mar. Ecol. Prog. Ser.* 294, 95–99.

Yunev, O. A., Vedernikov, V. I., Basturk, O., Yilmaz, A., Kideys, A. E., Moncheva, S., et al. (2002). Long-term variations in surface chlorophyll-a and primary production in the open Black Sea: changes in the pelagic ecosystem over the last decades. *Mar. Ecol. Prog. Ser.* 230, 11–28. doi: 10.3354/meps230011

Zaitsev, Y. P., and Alexandrov, B. G. (1997). "Recent man-made changes in the Black Sea ecosystem," in *Sensitivity to Change: Black Sea, Baltic Sea and North Sea*, eds E. Ozsoy and A. Mikaelyan (Dordrecht: Kluwer Academic Publishing), 25–31. doi: 10.1007/978-94-011-5758-2_3

Zibordi, G., Holben, B., Hooker, S. B., Mélin, F., Berthon, J. F., Slutsker, I., et al. (2006). A network for standardized ocean color validation measurements. *Eos.*, 87, 293–297.

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An Enhanced Ocean Acidification Observing Network: From People to Technology to Data Synthesis and Information Exchange

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A successful integrated ocean acidification (OA) observing network must include (1) scientists and technicians from a range of disciplines from physics to chemistry to biology to technology development; (2) government, private, and intergovernmental support; (3) regional cohorts working together on regionally specific issues; (4) publicly accessible data from the open ocean to coastal to estuarine systems; (5) close integration with other networks focusing on related measurements or issues including the social and economic consequences of OA; and (6) observation-based informational products useful for decision making such as management of fisheries and aquaculture. The Global Ocean Acidification Observing Network (GOA-ON), a key player in this vision, seeks to expand and enhance geographic extent and availability of coastal and open ocean observing data to ultimately inform adaptive measures and policy action, especially in support of the United Nations 2030 Agenda for Sustainable Development. GOA-ON works to empower and support regional collaborative networks such as the Latin American Ocean Acidification Network, supports new scientists entering the field with training, mentorship, and equipment, refines approaches for tracking biological impacts, and stimulates development of lower-cost methodology and technologies allowing for wider participation of scientists. GOA-ON seeks to collaborate with and complement work done by other observing networks such as those focused on carbon flux into the ocean, tracking of carbon and oxygen in the ocean, observing biological diversity, and determining short- and long-term variability in these and other ocean parameters through space and time.

Keywords: Global Ocean Acidification Observing Network, Sustainable Development Goal, ocean acidification, ecosystem stressors, capacity building

INTRODUCTION

The ocean has absorbed approximately 30% of anthropogenic carbon dioxide (CO_2) emissions since the industrial era began (Intergovernmental Panel on Climate Change (IPCC), 2013). Ocean acidification (OA), or the ongoing observed increase in marine acidity, is a direct result of this uptake (Doney et al., 2009; Intergovernmental Panel on Climate Change (IPCC), 2013). The average surface ocean pH has decreased by approximately 0.11 units from a preindustrial mean value of 8.17, this represents an increase of about 28% in hydrogen ion concentration (Intergovernmental Panel on Climate Change (IPCC), 2013). By the end of this century, surface ocean pH is expected to decline by another 0.1–0.4 units, and carbonate ion (${CO_3}^{2-}$) concentration is expected to decline by as much as 50% over the same period compared to preindustrial conditions (Feely et al., 2004; Orr et al., 2005; Doney et al., 2009; Gattuso et al., 2015).

Ocean acidification has the potential to impact marine organisms in a variety of ways, including effects from decreased pH, elevated partial pressure of CO_2 (pCO_2), and decreases in the calcium carbonate ($CaCO_3$) saturation state. Changes in the $CaCO_3$ saturation state (Feely et al., 2004) make conditions corrosive for many calcifying organisms such as many species of molluscs, corals, echinoderms, and calcifying plankton, with potential dissolution of calcareous structures such as shells or skeletons (Eyre et al., 2018; Harvey et al., 2018). Changing carbonate chemistry also impacts the process of calcification in many species (Kroecker et al., 2013; Albright et al., 2016; Bednaršek et al., 2017). Less direct impacts can occur where declines in calcification of key habitat forming organisms result in ecosystem shifts and loss of the structural complexity and biodiversity of coral reefs and other benthic communities (Fabricius et al., 2014; Sunday et al., 2016). Negative impacts of changing ocean carbonate chemistry have already been observed in calcifying organisms living in some regions of coastal upwelling where natural acidity is relatively high (Bednaršek et al., 2014, 2017). Research also suggests that changing ocean chemistry and reduced pH may affect the physiology, behavior, and population dynamics of many non-calcifying species (Doney et al., 2009; Gattuso et al., 2015).

Over the past decade, the OA research community has grown rapidly, and the number of publications related to OA has grown exponentially (**Figures 1**, **2**). In the context of this burgeoning growth, the ocean observing community recognized a need for global coordination at OceanObs'09 (Feely et al., 2010) and has since made progress on collaborative efforts. The potential impacts to marine ecosystems have resulted in OA becoming one of only ten targets for the United Nations (UN) Sustainable Development Goal (SDG) 14 on the conservation and sustainable use of marine resources. The World Meteorological Organization has also included OA as a headline climate indicator, recognizing the link to increasing atmospheric carbon dioxide concentrations and the climate system. The challenges facing OA researchers, current and future coordinating activities, and a vision in light of the upcoming United Nations Decade of Ocean Science for Sustainable Development (2021–2030) for future OA observing are discussed in this white paper.

CHALLENGE

The adaptive capacity of organisms that may be impacted by changing ocean chemistry is not well known, and a great deal of work must be done to understand the interactions of multiple stressors and their potential ramifications for marine ecosystems and the human communities that depend on their health. Further, while OA due to an increased atmospheric CO_2 concentration occurs in all marine waters, carbonate chemistry in coastal waters is affected by additional processes, such as nutrient addition and its effect on respiration, meaning that coastal acidification may be driven by more factors than just the increase in atmospheric CO_2.

The longest time-series observing assets to date have been deployed within several open-ocean environments where they have documented surface water pCO_2 values mostly tracking the long-term trend in rising atmospheric CO_2 (**Figure 3**), demonstrating that the global ocean carbon storage has increased since 2000 (Blunden et al., 2018; Feely et al., 2018; Le Quéré et al., 2018). Recent observations within shelf waters have been shown in some regions to lag atmospheric CO_2, indicating a tendency for enhanced shelf uptake of atmospheric CO_2 from the aqueous phase into biomass (Laruelle et al., 2018). Other coastal regions exhibit more rapid increases in pCO_2 relative to the open ocean, indicating more rapid acidification due to the additive effects of CO_2 uptake and increased upwelling (Chavez et al., 2017). Coastal seas have been suggested to have changed in the recent past from a net source to a net sink (Bauer et al., 2013; Fennel et al., 2018; Laruelle et al., 2018). The enhanced uptake of CO_2 by the ocean and shelves also changes the rate at which waters acidify, altering local rates of acidification, a process not well simulated by coarse global simulation models nor adequately captured by many direct measurements from the existing observing system. The local processes that govern these modifications may also serve to amplify (or dampen) global

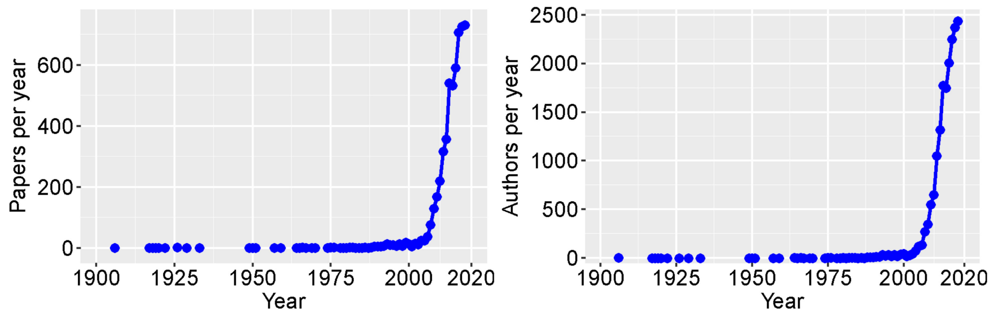

FIGURE 1 | Annual number of peer-reviewed publications on ocean acidification and number of authors involved during the period 1900–2018. Figure produced by Jean-Pierre Gattuso using the bibliographic database of the IAEA Ocean Acidification International Coordination Centre (OA-ICC).

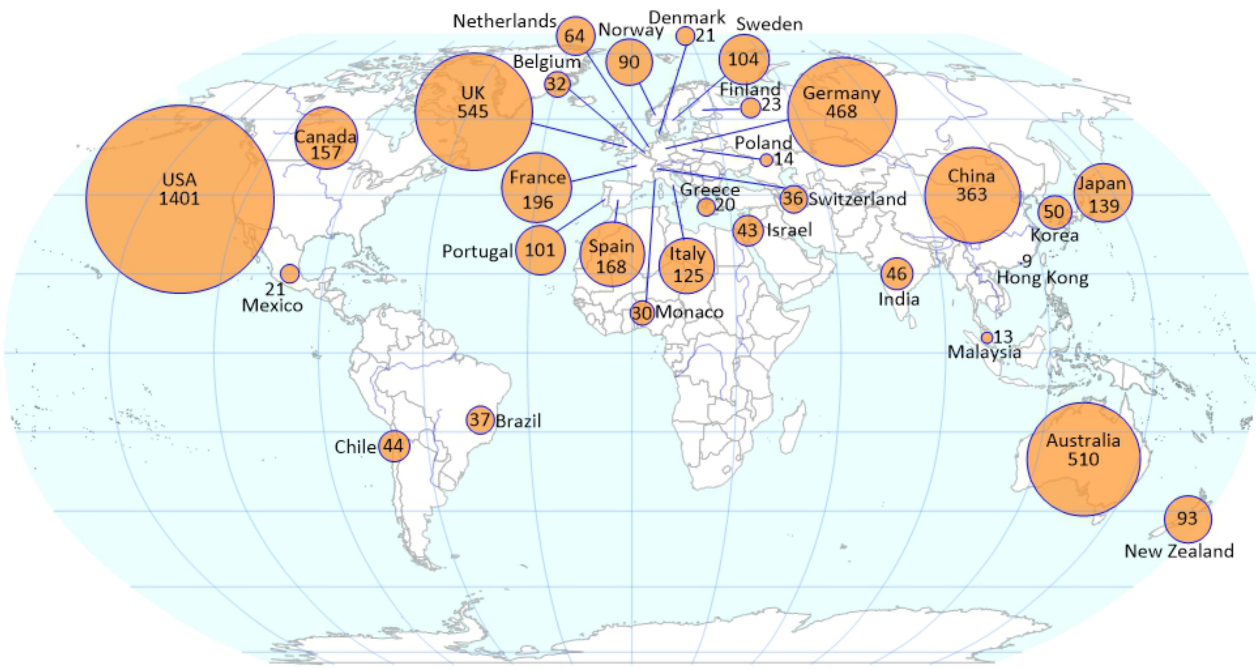

FIGURE 2 | Global distribution of ocean acidification publications by country, based on first author affiliation. Data from the IAEA Ocean Acidification International Coordination Centre (OA-ICC).

changes expected from global earth system model projections, potentially altering the ecological consequences for shelf systems.

In addition to variability in time, the rates of uptake of CO_2 from the atmosphere also vary spatially, especially in coastal and shelf seas (Fennel et al., 2018; Laruelle et al., 2018). The magnitude of the sink of carbon has been shown to vary latitudinally, with high latitude (north of 30°) coastal seas providing a sink while low latitude shelves are generally a source or neutral (Cai et al., 2006; Bauer et al., 2013; Chen et al., 2013). Spatial and temporal variability poses a challenge to the observational and modeling communities that could be better addressed with new tools and sensors, capabilities and technologies (see Next Generation Sensor Technologies to Enhance the Observing System), and through international collaborative efforts like GOA-ON. The scientific challenges that the coastal variability imparts on stakeholders, managers, coastal communities, and other marine resource end-users poses unique challenges for attribution science, habitat shift projections, and stress response timing for vulnerable ecosystems. Below we describe some of the new tools, capabilities, and technologies available to be ported through new informational products served through GOA-ON, as well as the empowerment this global network offers coastal communities.

NETWORK GENESIS AND CONTEXT

Ocean observation, monitoring systems, and networks are designed to quantify variability and long-term changes, and to discover natural dynamics and anthropogenic impacts. The

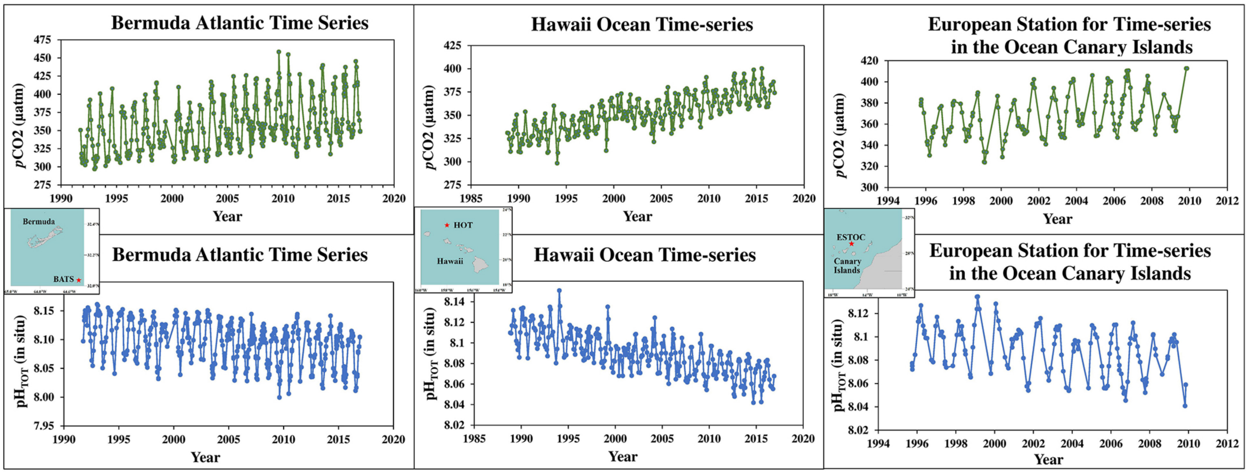

FIGURE 3 | Time series of *in situ* pCO_2 **(top)** and pH_T **(bottom)** for three time series stations in the Atlantic and Pacific Oceans. Data sources: BATS data: http://batsftp.bios.edu/BATS/bottle/; Hot data: University of Hawaii (http://hahana.soest.hawaii.edu/hot/products/HOT_surface_CO2; ESTOC data: https://www.nodc.noaa.gov/archive/arc0051/0100064/1.1/data/0-data/).

Global Ocean Observing System (GOOS), now considered the core, community-vetted ocean observing system for guidance, utilizes the Framework for Ocean Observing to implement an integrated and sustained ocean observing system (Intergovernmental Oceanographic Commission (IOC)-UNESCO, 2012). This systems approach is designed to be flexible and to adapt to evolving scientific, technological, and societal needs, helping to deliver an ocean observing system tailored to user needs and the mitigation of societal impact. Within this framework, OA is included as one phenomenon for inorganic carbon in the Essential Ocean Variables (EOV) suite[1].

The genesis of a global OA observing network with a multidisciplinary focus can be traced to an internationally authored OceanObs'09 community white paper, *An International Observational Network for Ocean Acidification* (Feely et al., 2010). This paper recommended "an integrated international interdisciplinary program of ship-based hydrography, time-series moorings, floats and gliders with carbon system, pH and oxygen sensors, and ecological surveys to determine the large-scale changes in the properties of ocean water and the associated biological responses to OA." Following panel discussions at OceanObs'09, the groundswell of scientists interested in this effort increased and broadened in discipline and expertise. In 2012, a workshop was held in Seattle, WA, United States, to design a global OA observing network that would delineate the physical–chemical processes controlling the acidification of the oceans and their large-scale biological impacts and was aligned with the EOV process. Workshop participants defined the goals and requirements of a global OA observing network in the context of responding to societal needs.

Outcomes of the Seattle meeting were community definition of the rationale, goals, design, suite of measurement parameters, data quality objectives, data distribution strategies, and integration with international programs (Newton et al., 2013). The rationale and design of the components and locations considered existing networks and programs and identified gaps in both open-ocean and coastal regions. The minimum suite of measurement parameters and performance metrics identified two different usage cases with the data quality objectives needed to support these: (1) "Climate" is defined as measurements of quality sufficient to assess long-term trends with a defined level of confidence. With respect to OA, climate-quality data support detection of the long-term anthropogenically driven changes in hydrographic conditions and carbon chemistry over multidecadal timescales. (2) "Weather" is defined as measurements of quality sufficient to identify relative spatial patterns and short-term variation, particularly in nearshore regions where variability is higher (**Table 1**). Weather-quality data support mechanistic interpretation of the ecosystem response to OA and understanding of local, immediate OA dynamics. The name, Global Ocean Acidification Observing Network (GOA-ON), was coined at the workshop[2].

GOA-ON serves three goals to (1) improve understanding of global OA conditions; (2) improve understanding of ecosystem response to OA; and (3) acquire and exchange data and knowledge necessary to optimize modeling of OA and its impacts (Newton et al., 2015). Thus, GOA-ON focuses on *both* chemistry and biology, and through its data portal[3], it provides discoverability of—and in some cases access to—data for myriad uses, including to improve forecast modeling and prediction of the future ocean.

The GOA-ON community held a second workshop in St. Andrews, United Kingdom, in 2013 to refine the vision for the structure of GOA-ON, with emphasis on defining monitoring

[1]GOOS EOV Suite: http://www.goosocean.org/components/com_oe/oe.php?task=download&id=35906&version=2.0&lang=1&format=1.

[2]GOA-ON website: https://www.goa-on.org.

[3]http://portal.goa-on.org/Explorer

TABLE 1 | Recommended measurement uncertainties for climate and weather from Newton et al. (2015).

Parameter	Climate Uncertainty	Weather Uncertainty
TCO_2	2 µmol/kg	10 µmol/kg
TA	2 µmol/kg	10 µmol/kg
pCO_2	2 µatm	10 µatm
pH	0.003	0.02
Aragonite Saturation	0.04	0.2
Calcite Saturation	0.06	0.3

for ecosystem impacts of OA in shelf and coastal seas (Newton et al., 2013). After this workshop, the development of a data portal commenced to provide OA-relevant asset locations and metadata, with a vision toward serving data products. The portal was made possible through an initial investment by the University of Washington and by leveraging existing capacity funded by the United States Integrated Ocean Observing System (U.S. IOOS). GOA-ON reached out to its members to populate the data portal, housed at the GOA-ON website, with their observing information.

At a third workshop in Hobart, Australia, in 2016, major outcomes were related to the building and reinforcement of communities to increase regional coordination, with identification of regional implementation needs, including information, data products, and capacity building. The GOA-ON mentorship program known as "Pier2Peer" (described below) was launched at this workshop. Regional OA networks, acting as regional hubs of GOA-ON, have emerged in Latin America, Africa, the Western Pacific, Europe, the South Pacific Islands, and North America. Advances have been made in capacity building, and the GOA-ON community has expanded to more than 600 members from 94 countries as of March 2019 (**Figure 4**). A fourth workshop in April 2019 in Hangzhou, China, targeted further development of a coordinated network and regional engagement. Workshop themes covered were ocean and coastal acidification in a multi-stressor environment; observing ocean and coastal acidification and impacts on ecosystems; modeling and forecasting ocean and coastal acidification and ecosystem responses; and focusing GOA-ON efforts for societal benefit, stakeholder needs, and capacity building.

The vision for the future of the global OA observing network, described in this white paper, is built around eight components: (1) Optimize GOA-ON to better inform modeling community needs; (2) Fill gaps in understanding of chemical changes and biological impacts; (3) Promote and advise the development of next generation sensor technology; (4) Support the growth of regional hubs and grassroots establishment of new hubs; (5) Expand and enhance capacity-building efforts to enable broader participation; (6) Improve the GOA-ON data portal; (7) Build OA networks producing scientific data and information designed to inform regional and international environmental action; and (8) Enhance collaboration with other observing networks.

GOA-ON REQUIREMENTS AND GOVERNANCE

Ocean acidification is a global issue, but it has local effects that differ depending on the environment (e.g., sensitivity of local species), and societal uses of the ocean and its resources. An approach that coordinates effort, so that global as well as local status could be assessed effectively and with consistent methods, was deemed necessary during the initial workshops held by GOA-ON. The OA data quality definition of Climate and Weather, based on data application, was an important step for GOA-ON. Many international or local climate assessments require climate quality data both in the open ocean and coastal seas (Karl et al., 2010). The inherent variability in coastal areas results in more

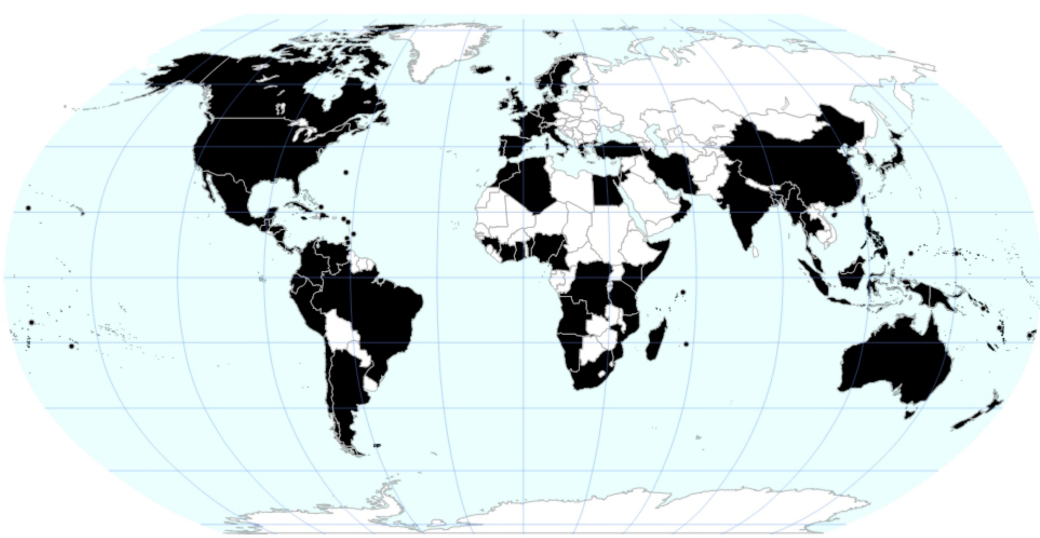

FIGURE 4 | Countries with GOA-ON members as of April 2019 are shaded black, excluding representatives of UN bodies.

years of climate-quality data being required to observe trends (Sutton et al., 2018) compared to the open ocean. Uses such as monitoring for aquaculture and biological experiments, or for interpretations of local mechanisms underlying temporal and spatial variation can be served by either weather-quality data or climate-quality data.

Three levels of measurements were defined for the two observational goals, with level 1 being critical measurements, level 2 enhanced measurements that allow further understanding, and level 3 those in development or experimental measurements. In general, it was much easier for the community to define requirements for goal 1, OA status, than for goal 2, ecosystem response. For the latter, the participants considered diverse environments, such as polar, temperate, tropical, nearshore, and coral habitats.

Goal 1 level 1 variables are: temperature, salinity, oxygen, depth, and carbon-system constraints. Carbon-system constraints are achievable in a number of ways, including combinations of direct measurements and estimates based on measurements of at least two carbon-system variables. Two further variables, fluorescence and irradiance, were considered important, except where the platform is not appropriate or available for such measurements. Goal 2 variables provide additional detail, and the "level" requirements are defined by usage. In general, these include the goal 1 variables named above, plus variables describing phytoplankton, zooplankton, benthic producers and consumers in shelf seas and nearshore, nutrients, organic carbon and nitrogen, and microbial measures.

The outcome from the GOA-ON vision and plan is to enable globally accessible high-quality data and data synthesis products that facilitate research and new knowledge on OA, communicate the status of OA and biological response, and enable forecasting of OA conditions. End-uses of these data include support for the development of national and international policy and adaptive action, including those related to carbon emission policies, food security and livelihoods, fisheries and shellfish aquaculture practices, protection of coral reefs, shore protection, cultural identity, and tourism. However, investment in capacity in multiple areas critical to meet these needs must be addressed, including physical observing infrastructure, operations and maintenance, data QA/QC, analytical and synthesis activities, and the intellectual infrastructure.

Since the launch of the Global Ocean Acidification Observing Network in 2013, forward momentum has been maintained by an Executive Council of experts from around the world who either represent core scientific disciplines or international or national institutions with a leadership role in the network. A distributed secretariat was established in 2018 with support from the International Atomic Energy Agency, the Intergovernmental Oceanographic Commission, and the U.S. National Oceanic and Atmospheric Administration (NOAA) Ocean Acidification Program. The secretariat has a key role in the development of GOA-ON through the coordination and communication of activities and in building science-policy linkages. The data portal and website services are also part of the distributed secretariat, supported by NOAA's Ocean Acidification Program, U.S. IOOS, and the University of Washington.

STATUS OF THE OBSERVING NETWORK

The observing network cataloged and guided by GOA-ON represents a multinational coordination effort to harmonize ocean observing strategies aimed toward acquiring robust evidence on OA and its worldwide impacts, guiding management action from regional to international levels, and informing policy decisions. Participating scientists adhere closely to the established observing requirements detailed in the GOA-ON Requirements and Governance document (Newton et al., 2015), which is oriented around the three goals outlined in Section "Network Genesis and Context" of this paper. In accordance with these requirements, the existing observing network is composed of assets deployed across multiple ecosystem domains ranging from large-scale open-ocean regions to coastal environments inclusive of large estuaries and embayments. Assets deployed by GOA-ON participants are located in ecosystems as divergent as the Arctic pelagic seas to tropical coral reefs and use of a broad range of asset types from ship-based sampling to diver collection teams. Perhaps the most unique aspect of the GOA-ON observing network is the emphasis on interdisciplinary observations including carbon chemistry, meteorology, oceanography, biogeochemistry, ecology, and biology. The goal is not only to track OA, but also to understand and monitor the ecological changes that may result, and this sets GOA-ON apart from many other observing systems.

One example of this transdisciplinary approach is the strategy employed in coral reef monitoring. NOAA established a coordinated national coral reef monitoring strategy that includes a broad suite of OA-relevant ecological metrics, including the adoption of standardized Calcium Carbonate Accretion (CCA) and bioerosion indices, which are deployed in tandem with regular carbonate chemistry monitoring (pCO_{2sea}, pCO_{2air}, and pH) together with temperature, salinity, oxygen, fluorescence, and turbidity. The protocols and methods adopted by NOAA for coral reef OA monitoring have since been shared with the international community through a series of workshops that have fostered the adoption of similar methods throughout Western Pacific nations and elsewhere.

The current GOA-ON observing network[4] is composed of 598 assets deployed around the world and supported by 54 nations. The assets include 247 ship-based time series, 151 moorings, 118 fixed ocean time series, 30 repeat hydrography lines, and 22 volunteer observing ships (**Figure 5**). However, only about two thirds of the reported assets include dual measures of the carbonate system, which is a necessary minimum prerequisite for fully constraining the system as called for under the GOA-ON requirements. Only about 30% of the assets on the portal have associated links to open-access data.

Many of the assets are deployed in specific open-ocean locations and along coastal and shelf margins that are likely to be heavily impacted by coastal biogeochemical processes. This makes direct detection of OA more challenging, particularly in the absence of suitable regionally scaled biogeochemical models that can be used for ascribing the specific drivers behind

[4] http://portal.goa-on.org/Explorer

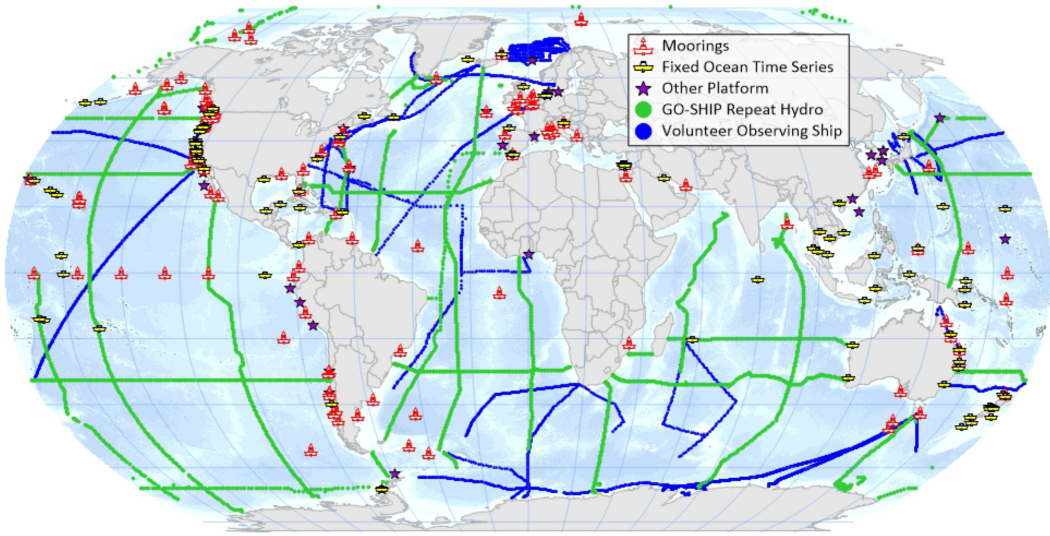

FIGURE 5 | Present-day (as of April 2019) Global Ocean Acidification Observing Network which is collaborative with the GO-SHIP, Ocean SITES, SOCONET, SOOP communities and other open-ocean and coastal observing networks.

the observed carbonate dynamics. Furthermore, many of the impacted harvestable marine species reside below the mixed layer depth while most of the observing system data to date are from the surface waters due to limited availability of sensors suitable for deep-water deployment.

The observing design is working increasingly toward collecting biological data from the field to determine if impacts predicted based on laboratory experiments are occurring in the natural environment. This includes the use of standardized CCA accretion plates in the field to determine if CCA rate changes identified in experiments are occurring in coral reefs. Almost half of the assets currently listed on the GOA-ON portal are measuring at least one biological variable (chlorophyll, cyanobacteria/bacteria, zooplankton, and/or phytoplankton). New monitoring indices such as pteropod shell condition are also being explored using repeated ship-surveys along the U.S West Coast. The identification of additional biological variables and integration into the network through cooperation with existing biological observing programs is discussed in the following section.

A VISION FOR THE OCEAN ACIDIFICATION OBSERVING NETWORK

The observing network should be optimally configured to meet modeling community needs and be fit to purpose. As detailed in the GOA-ON requirements (Newton et al., 2015), the purpose can include detection of OA, whereby assets should be deployed where anticipated time of emergence (ToE) of an OA signal above background natural variability occurs within a few decades in terms of biogeochemical changes, and within perhaps several decades in the case of ecological monitoring (Sutton et al., 2018). This detection requires "climate-quality" data, which involves a more stringent accuracy and precision than may be needed for some applications (**Table 1**). Models can also assist with determining this metric as long as the primary processes driving the carbonate dynamics are suitably constrained. A well validated or data-assimilated model can be used to extend observations into the past and future. Global-scale models have been used to predict the ToE of an OA signal against the background of other environmental changes (e.g., Gruber, 2011; Carter et al., 2016, 2017; Henson et al., 2017; McKinley et al., 2017). High-resolution coastal models that connect large-scale open-ocean conditions with changes in coastal regions, including coastal upwelling and coral reef systems, are beginning to emerge (e.g., Mongin et al., 2016; Siedlecki et al., 2016; Turi et al., 2016).

In locations where the purpose of an OA observing asset is to monitor current conditions, the less stringent "weather-quality" constraints (**Table 1**) may meet requirements. The observing asset in this case should include a suite of observations that can adequately characterize biogeochemical OA conditions most relevant to applications such as near-real-time support of industry products. Examples include observing systems deployed at shellfish hatcheries at a number of facilities in the U.S. Northwest and Northeast (Barton et al., 2015). This level of data is often available in near-real-time, making it a vital part of forecast evaluation and a key locus of interaction with stakeholders in coastal communities.

Additionally, non-sustained deployments should be considered in cases where heuristic algorithm development or mechanistic determinations are the aim. Observing initiatives designated for the purpose of characterizing the primary modes of variability and characterizing it by means of algorithm development and constraint can prove very valuable in scaling direct observations in both time and space. Examples might include flux and rate measurements such as at the benthic interface or investigating mechanisms of predictability to enable forecast system development, perhaps by exploring the ways in which large-scale climate variability is communicated to regional waters and watersheds.

Observing technologies are becoming more autonomous and highly resolved in time and space, which allows observing networks to become better connected with the coasts and thus communities impacted by the changing ocean. The design and implementation of networks require them to be adaptable, so they are able to continue to evolve with emerging technologies as they become available. Coastal communities will be increasingly affected by changing ocean conditions and forecasts and real-time data access will enable them to develop strategies to respond. The co-location of chemical and biological measurements is needed to assess *in situ* impacts and helps build the capacity to develop indices, metrics, and risk assessment for coastal ecosystems (Boyd et al., 2015; Bednaršek et al., 2016). The same observing infrastructure should also provide or coordinate with measures of other stressors including temperature change, hypoxia, and pollution that can amplify or attenuate OA responses and influence the physiology, ecology, and the adaptive capacity of marine organisms (Hurd et al., 2018).

Next Generation Sensor Technologies to Enhance the Observing System

The GOA-ON goal of improving our understanding of global OA conditions will be strongly supported by the development of new sensor technology. Specifically, new technology is needed to quantify (1) the range of natural variability in diverse marine ecosystems (e.g., **Figure 6**) (Harris et al., 2013); (2) the organismal response to different biogeochemical conditions (Boyd et al., 2015); and (3) long-term trends in biogeochemical parameters. A wide range of *in situ* measurements are desired but those focused on stressors, i.e., temperature, pCO_2, inorganic carbon and pH, oxygen, nutrients, salinity (Breitburg et al., 2015), and biology (biomass, populations) (McQuillan and Robidart, 2017) are high priorities, as discussed in Section "GOA-ON Requirements and Governance." Accordingly, 10 years ago, OceanObs'09 papers (Borges et al., 2010; Byrne et al., 2010; Feely et al., 2010) called for the development of autonomous sensors and systems to quantify dissolved inorganic carbon (DIC) and total alkalinity (TA). There has been significant progress in this direction with successful *in situ* deployments of novel DIC and TA instruments (Spaulding et al., 2014; Fassbender et al., 2015; Wang et al., 2015). However, as stated in Byrne et al. (2010), "*There are at least two principal impediments to widespread utilization of in situ instrumentation: cost and complexity.*" These challenges remain and have limited the widespread use of the new devices.

Moreover, even for technologies that have been on the market for several years, data quality varies substantially based on the experience level of the operators (McLaughlin et al., 2017). Continued opportunities for hands-on training, a task that is often initiated by scientists themselves, will be necessary for high-quality data collection and widespread use of new and complex devices. Co-deployment with independent sensors is recommended for new technologies (Bresnahan et al., 2014; McLaughlin et al., 2017), further increasing the cost of obtaining high-quality data.

Sensor drift, or loss of accuracy over time, is also a persistent problem. Even when accuracy requirements are relaxed, e.g., for weather quality data in a hatchery, confidence within a defined tolerance must be established. Ideally, sensor data should be validated with independent, *in situ* samples. Often, conventional methods based on bottle samples collected before and after deployment do not provide sufficient replicates to confidently constrain sensor accuracy. Two highly advanced and widely utilized sensors use innovative strategies to correct for drift. Optode-based O_2 sensors, a technology that is considered to be mature, have been calibrated by exposing the sensors directly to air (Bittig and Körtzinger, 2015; Bushinsky et al., 2016). ISFET-based pH sensors use deep-water pH values as a pH standard for drift correction (Johnson et al., 2017; Williams et al., 2017). Without these drift corrections for O_2 and pH, the measurements would not be able to quantify the small seasonal changes in open ocean environments.

Simplified technology may be on the horizon. Promising new sensors for pH and pCO_2 are being developed based on optode time-resolved fluorescence technology similar to O_2 optodes (Clarke et al., 2015, 2017). Inexpensive, low-power infrared CO_2 sensors are now being used for oceanographic applications (Bastviken et al., 2015; Hunt et al., 2017). A miniature electrochemical sensor for combined measurements of pH and TA has recently been demonstrated (Briggs et al., 2017).

Deployment platforms are more sophisticated and able to accommodate a wider array of sensor technologies (Riser et al., 2018). Profilers include free drifting subsurface floats (Mignot et al., 2018), biogeochemical Argo profilers (Williams et al., 2017, 2018), ice-tethered (wire climbing) profilers (Toole et al., 2011), and moored profilers (e.g., winch operated; Palevsky and Nicholson, 2018). Autonomous underwater gliders and vehicles, self-propelled surface gliders such as Saildrone, and free-floating surface drifters are also becoming more common for oceanographic research in regions not readily accessible by research ships (Lindstrom et al., 2017). Cabled networks with power and high bandwidth data transmission might also become more common in the future. The adaptation of existing sensor technology to more diverse platforms is likely to continue to advance GOA-ON objectives. One additional area that is likely to improve is in our handling of big data sets, both in terms of quality control and the ability to provide real-time diagnostics (Duarte et al., 2018).

While it is likely that we will be able to more readily quantify the inorganic carbon system in the coming decade, other important parameters remain out of reach. Dissolved and particulate organic carbon are two critical pieces of the carbon cycle that might be affected by OA (Egea et al., 2018). Optical measurements (fluorescence, absorption) of colored dissolved organic matter are useful proxies (e.g., Jørgensen et al., 2011), but a direct measurement of dissolved organic carbon (DOC) that can be applied to a wide range of marine environments is needed.

A major objective of GOA-ON is to quantify relationships between marine organisms and stressors. While most research on biological impacts of ocean change is based on IPCC

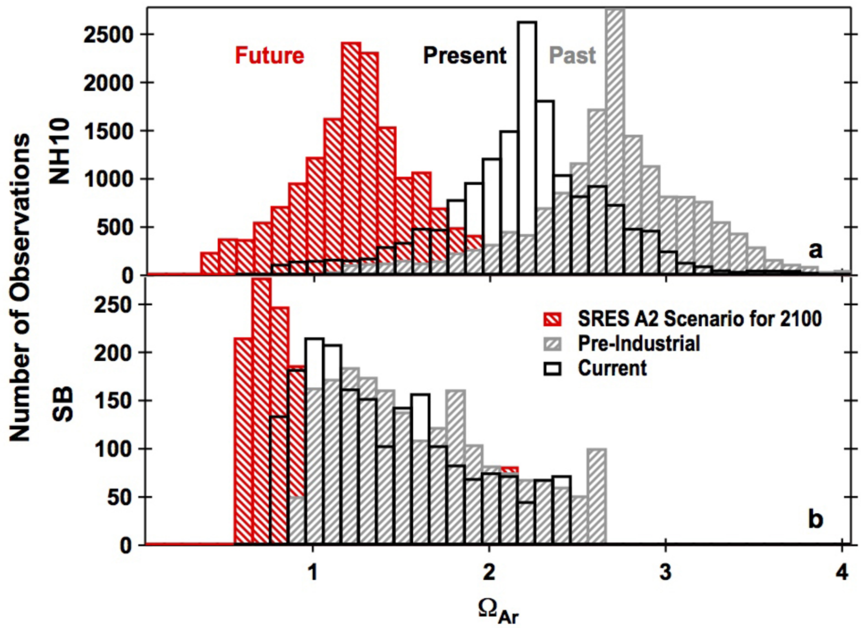

FIGURE 6 | (Top) Distribution of aragonite saturation data (open bars) calculated from in situ pH and pCO_2 measurements collected over 5 years at the Newport Hydrographic Line mooring (NH-10) off the Oregon coast (United States). The gray and red bars represent estimates from these data using pre-industrial and future CO_2 levels. **(Bottom)** The saturation states at the Oregon shelf break at 116 m depth. Adapted from Harris et al. (2013).

predictions, new sensor technology reveals existing spatio-temporal complexity of the marine environment that often exceeds the envelope of predicted change (Harris et al., 2013). The variability can influence species responses to baseline changes (Boyd et al., 2016). In addition, and particularly regarding marine benthic organisms, seawater physics and chemistry may significantly vary across small microclimates within habitats. Deployment of arrays of multiple sensors may help characterize these systems (e.g., Leary et al., 2017). Combining sensor data with biology remains an important but very young area of research, and often requires interdisciplinary collaborations or advanced training. New *in situ* sensor technology might make this more feasible. Future exciting opportunities exist to combine biogeochemical and physical measurements with sophisticated autonomous bio-analytical systems that can characterize and quantify microbial populations (e.g., automated flow cytometry, Hunter-Cevera et al., 2016; *in situ* genetic analysis, McQuillan and Robidart, 2017). These approaches can potentially overcome the challenge of connecting species biomass or composition with environmental variables by continuously monitoring over a wide range of conditions (Marrec et al., 2018).

The discussion above poignantly reveals the challenges we face in developing new biogeochemical and biological sensors. Repeated "technological revolutions" have made us believe that technology will continue to advance indefinitely. Sensor transduction mechanisms, e.g., optical or electrochemical transduction, are mature. Most oceanographic sensors have utilized building blocks from other areas (e.g., fiber optics, integrated circuits) in a combinatorial evolution (Arthur, 2009) to make oceanographic sensors. New building blocks from material science, molecular biology, miniaturization, and fluidics are likely (e.g., Briggs et al., 2017) but will there be new transduction mechanisms that we do not know of today?

Filling Gaps in Understanding of Biological Impacts

Addressing OA to minimize impacts requires the development of a mechanistic understanding of biological effects. In turn, understanding shifts in ocean biodiversity due to global change requires inclusion of "ocean weather" such as daily and seasonal variability in ocean chemistry, including changes in that variability due to OA (Bates et al., 2018). GOA-ON's second goal calls for a greater understanding of biological impacts and strong coordination of this research. Reviewing the requirements for biological observations as outlined in Newton et al. (2015), and bridging present and future variability in the carbonate system with ecosystem changes are the objectives of the GOA-ON biology working group. This group works toward three main tasks:

Task 1: Inform the Chemical Monitoring Program About the Biological Needs

Marine organisms are often living in highly fluctuating environmental conditions and experience an even wider variability through migrations, changes of environment at different life-history stages or manipulation of their niche. Through local adaptation, species and ecosystems are often able to survive the wide range of variability while stress is induced in conditions deviating from present environmental conditions (Vargas et al., 2017). We need to better capture all the aspects of this variability; for example, predicting organism sensitivity and identifying relevant future scenarios important for determining appropriate laboratory treatments require capturing the yearly pH regime experienced by an organism, including extremes, such as the minimum value experienced.

Task 2: Evaluate the Needs and Requirements of a Biological Monitoring Program

Identifying which biological variables to track as indicators of OA impact is extremely challenging. Traditional biological monitoring programs tend to focus on identifying, counting, or weighing particular taxa or communities (Bednaršek et al., 2014; Gattuso et al., 2015). As the identity of these organisms and the subsequent structure of communities differs greatly from place to place, it is difficult to identify key marine species or community types that can be monitored everywhere. Instead, the GOA-ON biology working group is aiming to identify ecosystem-level indicators that are likely to be impacted by OA, such as biogeochemical biomarkers of acidification and other stressors.

Task 3: Develop a Theoretical Framework Linking Chemical Changes to Biological Response

Forecasting biological impacts is one of the most pressing and important challenges in the field of OA. An understanding of what is driving biological responses to OA is critical as input to biological and ecological models that allow us to expand from existing monitoring initiatives to a more comprehensive biological response understanding. Using existing literature and a theoretical framework such as the niche theory, the GOA-ON biology working group is developing a probabilistic approach aimed at identifying the species, ecosystems, and sites that are the most at risk.

COORDINATION AMONG OCEAN OBSERVING NETWORKS

The existing large-scale oceanic carbon observatory network of the Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP) surveys, the Surface Ocean CO_2 Observing Network (SOCONET), the Ship of Opportunity Program (SOOP) volunteer observing ships, and the Ocean Sustained Interdisciplinary Time-series Environment observation System (OceanSITES) time-series stations in the Atlantic, Pacific, and Indian Oceans have provided a backbone of observations of the carbonate chemistry needed to address the problem of OA. These activities are linked through the International Ocean Carbon Coordination Project. Much of our present understanding of the long-term changes in the carbonate system is derived from these repeat surveys and time series measurements in the open ocean (Feely et al., 2004; Sabine et al., 2004; Carter et al., 2017; Williams et al., 2017). Enhancing these activities and expanding the global time-series network with new carbon and pH sensors, particularly in the Southern Hemisphere, is providing important information on the changing conditions in both open-ocean and coastal environments that have been extensively under-sampled in the past. At present, many of the existing moored carbon observatories only measure pCO_2 in surface waters, which is of itself insufficient to constrain the carbon system adequately for effective monitoring and forecasting OA conditions and the concomitant biological effects. Future efforts will require additional observations with an enhanced suite of physical, chemical, and biological sensors in the ocean.

The GOA-ON has been designed to be fully integrated and collaborative with other large-scale ocean carbon observing networks cited above by enhancing these networks with additional measurement capabilities, including additional sensors, data assimilation and distribution of resources via the GOA-ON data portal and linking them with coastal observing networks that also address OA. The resulting network design is coordinated to link existing efforts with a common resources, infrastructure, data, and modeling capabilities (**Figure 5**).

GO-SHIP plans are being augmented to include full water column and underway pH measurements on every cruise (Sloyan et al., in review). Plans for further expansion include the addition of biological and bio-optical measurements for estimating primary production, carbon export, and species changes. The SOCONET and SOOP networks, including volunteer observing ships and moorings, are also being expanded to include pH and other carbon system parameters where practical (Wanninkhof et al., in review), and many OceanSITES moorings have been outfitted with pH, pCO_2, and other biogeochemical sensors. Data integration, validation, and dissemination will continue to be implemented through the Surface Ocean CO_2 Atlas (SOCAT), the GLobal Ocean Data Analysis Project (GLODAP), and GOA-ON data portals.

Biological observations addressing the impact of OA ought to be framed within existing efforts, such as the Marine Biodiversity Observation Network (MBON). The Group on Earth Observations and MBON have worked together to define Essential Biodiversity Variables and GOOS has developed 'Biology and Ecosystem' Essential Ocean Variables (Miloslavich et al., 2018; Muller-Karger et al., 2018). Synergistic effort among the biological and OA communities by bringing experts together to discuss a common set of core variables to gain a more consistent and informed understanding of biological responses to OA is encouraged. Equally important will be the joint responsibilities of capacity building, mentoring, data delivery and outreach activities similar to those implemented by GOA-ON and partners and described in Sections "Data Access Through the Global Data Portal" and "Capacity Building and Regional Coordination."

Future plans for enhancement of the GOA-ON network include new observational time-series sites, new technologies, particularly autonomous observing platforms such as Saildrones and Biogeochemical Argo floats in both open-ocean and coastal locations, and the development of new modeling tools and data synthesis products for depicting global and regional trends in acidification and associated responses of marine food webs and ecosystems. Integration with emerging observing networks like the Global Ocean Oxygen Network will provide a global focus on understanding multiple stressor impacts and feedbacks. By combining observational capabilities wherever feasible we will be better positioned to provide integrated information on the combined effects of acidification and deoxygenation to scientists, stakeholders and the interested public.

DATA ACCESS THROUGH THE GLOBAL DATA PORTAL

The GOA-ON data portal provides an overview of where and how OA is measured and provides capability to access and visualize data and synthesis products. The inventory of assets can be searched interactively by region, platform type and variables, and observation-based products include contoured worldwide data such as pH, aragonite saturation, and total CO_2 from GLODAP and annual and decadal CO_2-weighted fugacity from SOCAT. Icons are used to display observing assets, many of which include links to data and metadata and some display real-time data. Observing assets include both stationary platforms such as fixed time series, moorings, and mobile platforms such as repeat hydrography, ship-based time series, and volunteer observing ships. For a given carbonate chemistry-measuring asset, the metadata include information on which parameters are measured and are linked to data providers, and other details.

Open and public access to data is a central tenet for increasing OA knowledge. Many members of GOA-ON who have provided coordinates for OA data-relevant observing platforms also provide access to the data from those platforms. A significant challenge is to facilitate better access to data in regions that overlap with the Exclusive Economic Zone (EEZ) of nations that restrict data access, declaring the information too sensitive to share. These EEZ regions may be sites of large variability and change, and they are potentially high risk for OA impacts on ecosystems and populations. GOA-ON will be working to facilitate data access in all regions.

Improving the Data Portal

There are several ways to add value to how the GOA-ON Data Explorer portal visualizes products from local to global scales. For example, the Data Explorer shows calculated aragonite saturation state (Ω), a biologically relevant value, for a few of the near real-time moorings. NOAA Pacific Marine Environment Laboratory has provided interactive box plots of monthly averaged aragonite saturation and pH, with pie charts showing the percent of time the measurements are below a given threshold value. The interactive feature of these plots allows for the pH or aragonite threshold to be adjusted up or down by the user. Thus, quantitative information on habitat suitability for different species with individual tolerances can be observed. This same approach can be expanded to other fixed assets with time series data. Another example is to utilize models of OA conditions that are calibrated and verified by observing data, providing regional and local forecast model output that can identify habitat suitability patterns in space and time. User confidence in the model output will be increased by a feature such as a "comparator" to compare model output and mooring data. Such a feature was developed by the U.S. IOOS' Northwest Association of Networked Ocean Observing Systems (NANOOS)[5] on their Data Explorer, which can be adapted to the portal. These two suggestions are within the current capability of the portal to serve, but dependent on output from scientists who maintain and develop models and moorings. However, support to maintain and develop the models, moorings, and analyses is required and often lacking.

New products that synthesize data are needed to provide information on status and trends, summary statistics, and graphics that are suitable for managers, policymakers, and the public. International buy-in and creative development are core needs for the portal development. GOA-ON envisions its data portal to be serving rather than archiving data, and to leverage and collaborate with the International Oceanographic Data and Information Exchange (IODE), National Oceanographic Data Centres (NODCs), and international data holdings, applying the metadata and data formats developed for the UN SDG 14.3.1 reporting process (discussed in more detail in Section "2030 Agenda") and other national and regional data centers. The visualization of 14.3.1 data provided by UN member states via the GOA-ON portal will be a direct service to scientists, policymakers and stakeholders.

During the next decade it will be necessary to develop tools and mechanisms to illustrate current and projected impacts of OA on marine life (GOA-ON Goal 2). Collaborative efforts between GOA-ON, GOOS, and subject-specific efforts such as the Ocean Biogeographic Information System (OBIS) and Intergovernmental Oceanographic Commission (IOC) Working Group 'International Group for Marine Ecological Time Series' (IGMETS), can be used to collect related data and information. Interoperability so that synthesis products can pull in both chemical and biological data is imperative. Producing such tools and visualization products will take substantial effort but doing so is at the heart of what society and scientists need; a way to easily view OA and ecosystem response.

CAPACITY BUILDING AND REGIONAL COORDINATION

Building capacity is essential to fill gaps in regions where there are few observations and research on OA, but where OA could have major consequences for livelihoods. Training courses focusing on resource-limited countries have been organized through collaboration among GOA-ON, the International Atomic Energy Agency's Ocean Acidification International Coordination Centre (IAEA OA-ICC), the US-based non-profit The Ocean Foundation, the Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO), and partners from the scientific community, local and regional stakeholders. Over 40 capacity building opportunities held since 2012 have trained over 480 researchers from 69 countries (**Figure 7**). The opportunities have ranged from training courses to regional coordination workshops, to support for participation in international conferences. The training courses have varied

[5]www.nanoos.org; Data Explorer: http://nvs.nanoos.org/.

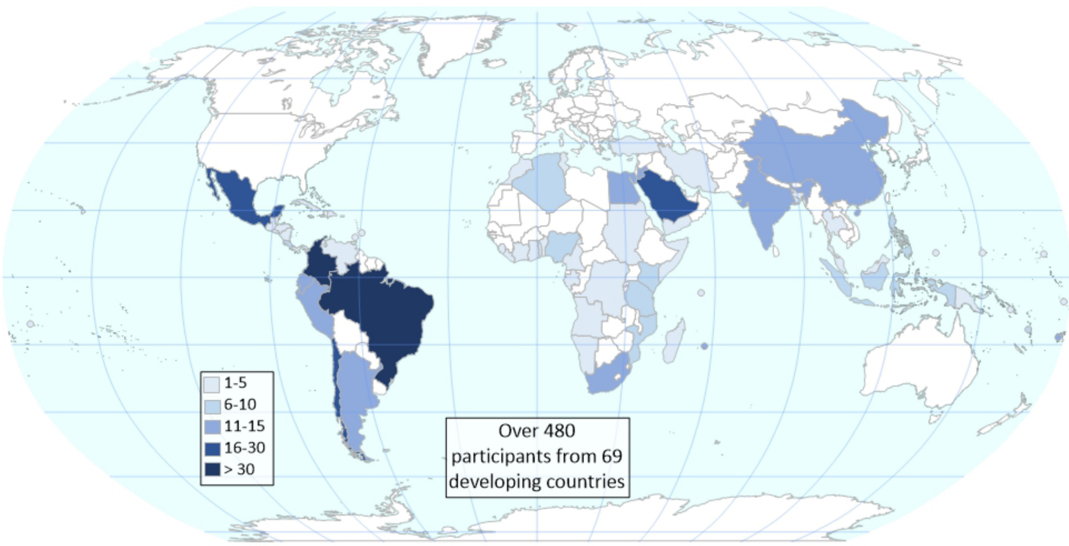

FIGURE 7 | Location and number of participants from developing countries involved in OA training workshops from 2012 to 2018.

in focus (e.g., chemistry, biology, data management) and level (basic to more advanced) depending on regional needs and have been adjusted in response to feedback from participants from early courses. Additional resources have also been developed [e.g., databases[6], 'Best practices' documents, online discussion fora (OAIE[7]), e-learning tools, etc.] to reach a wider audience and for sustaining OA research after the courses.

The lack of availability of instrumentation has hampered the establishment of sustained measurements for many countries and research organizations. In response, simplified methods and kits of equipment to measure weather-quality pH and TA, known as 'GOA-ON in a Box'[8] have been developed[9], with The Ocean Foundation providing kits to fifteen countries in Africa, the Pacific Small Island Developing States and the Caribbean.

GOA-ON also launched the Pier2Peer mentorship program in 2016 to facilitate one-on-one collaborations through direct transfer of expertise and advice by matching experienced researchers with early career researchers. Pier2Peer includes 93 mentees from 50 countries and 62 mentors from 15 countries. Although the program does not have dedicated funding, it has benefitted from a scholarship program organized by The Ocean Foundation[10], which has provided some funding for training visits and the establishment of new monitoring programs. The mentoring process has helped develop close working relationships between early career researchers and experts from many institutions, and the feedback on small grants applications associated with the Pier2Peer program has been an effective way to encourage better grant writing skills.

[6]OA-ICC databases: https://www.iaea.org/services/oa-icc/science-and-collaboration/data-access-and-management.

[7]The Ocean Acidification Information Exchange: https://www.oainfoexchange.org/.

[8]https://www.oainfoexchange.org/teams/GOA-ON-Community

[9]https://news-oceanacidification-icc.org/2016/10/21/iaea-int7019-task-force-meeting-on-the-development-and-standardization-of-methodology-12-14-october-monaco/

[10]https://www.oceanfdn.org/projects/hosted-projects/ocean-acidification

A Vision for Enhancing and Expanding Capacity Building

Capacity building, including training, mentorship, and providing access to equipment is a priority for the GOA-ON community in recognition of the strong disparity among scientific capabilities across the globe. Tracking how global capacity changes over time will be critical, especially to know whether scientists in resource challenged countries are able to maintain monitoring over time with their respective country's support (**Figure 8**).

Future fundraising strategies will rely on an ongoing communications effort that showcases both the power of a global network and the uses for local data. The resources raised might support both regional trainings, including data management, and new scientific projects advanced through Pier2Peer proposals.

Beyond maintenance and improvement of fundraising and institutional support, the strategy for capacity building operations in the next decade will focus on enhancing the network and the direct exchange of expertise and technology at national, regional, and global levels. The facilitation of direct interaction with established scientific experts through workshops and mentorships has been one of the most successful components of GOA-ON, and it is relatively low-cost. Encouraging collaboration and exchange of knowledge between peers as well as experts has also been highly successful and will continue to be a cornerstone of capacity building.

The establishment of regional centers of excellence for sample analyses and training are possibilities, including the development of more advanced training in data quality control to ensure high-quality data sets are made available through publicly accessible platforms and eLearning resources. Equally important is the

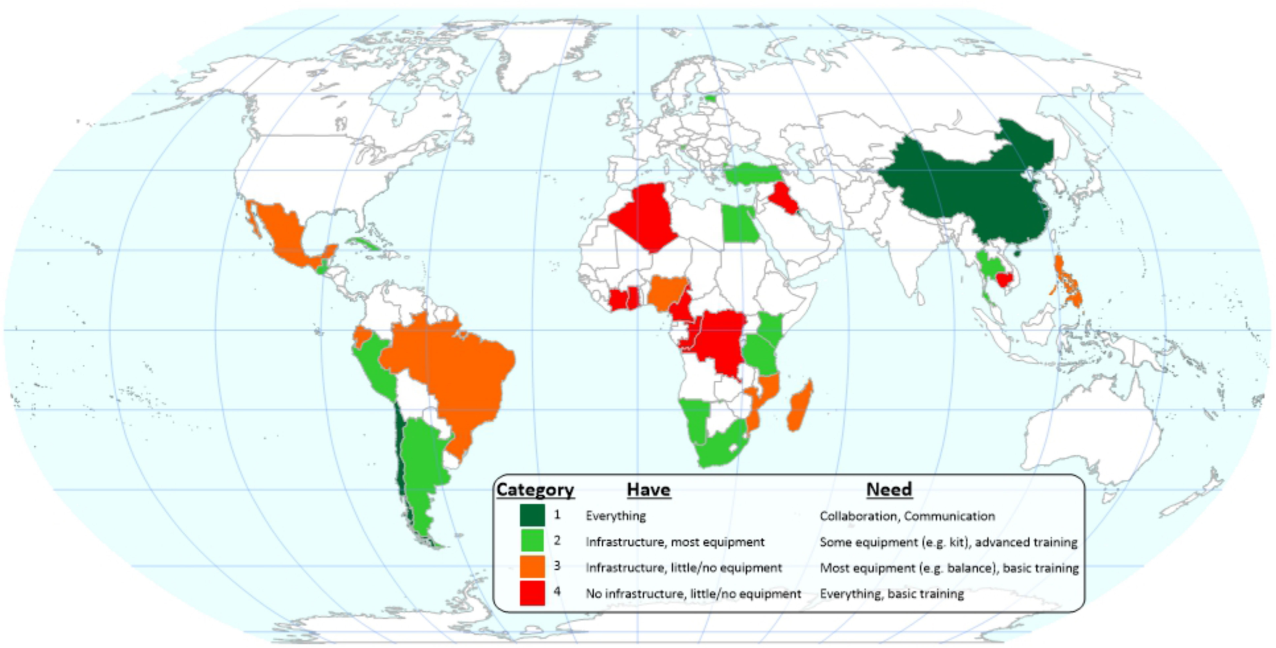

FIGURE 8 | Results from a gap analysis survey of in-country researchers by the IAEA, TOF, IOC-UNESCO, NOAA and others in 2016 to assess the status of a developing country's ability to monitor OA or track its effect on relevant marine resources.

identification of data-serving platforms (or proposals to create new ones) so that every scientist, regardless of country, has an online repository for serving of data.

Capacity building and training workshops have also identified a number of technical challenges to address. The development of low-cost and simple-to-use equipment, such as handheld spectrophotometric pH analyzers, will be essential for the ongoing success of this work. The sustainable production of certified reference materials covering a range of salinities from estuaries to the open ocean and the provision of purified pH indicator dyes that are affordable and accessible are common requirements for the community.

The demand for training from developing countries and access to appropriate technology is expected to increase in the next decade as many countries begin to report toward SDG 14.3.1, which is discussed in detail in Section "2030 Agenda." GOA-ON's role in coordinating and providing capacity building will be increasingly important to make sure that limited resources are used in the best way possible. Periodic assessment through surveys of both the effectiveness and long-term sustainability of these efforts, which were initiated with regional and/or international funds, will rely on networks like GOA-ON.

The Importance and Future Role of Regional Hubs

Regional networks or "hubs" are an essential component of GOA-ON's operating structure because they allow for geographically-specific coordination and local expertise to address needs and gaps in OA monitoring. The hubs are formed in a grassroots manner and are self-governing with GOA-ON providing advice and support and a representative of each hub serves on the Executive Council. Seven hubs are currently providing opportunities for regional networking, collaboration, training, and the identification of region-specific priorities and scientific gaps: LAOCA[11], the IOC-WESTPAC OA Program[12], the OA-Africa Network[13], and the North American Ocean Acidification Network[14], the Pacific Islands and Territories Ocean Acidification network (PI-TOA)[15], Northeast Atlantic[16], and Mediterranean hubs[17].

Two priority areas for future hubs are the Arctic and Southern Oceans. These are regions where biological impacts due to OA may already be occurring (Kawaguchi et al., 2013; Bednaršek et al., 2016; Rastrick et al., 2018) and the skill of models in predicting changes are least certain (Lenton et al., 2013; Kwiatkowski and Orr, 2018).

Regional hubs will continue to be essential for meeting future needs for GOA-ON's three goals. Local and regional collaboration is easier to maintain logistically, encourages collaboration among scientists studying the same or adjacent ocean and coastal systems, and coordinates localized knowledge of potential socioeconomic impacts. OA is progressing differently across various coastal areas and regions; therefore, it is important

[11]http://laoca.cl/en/
[12]http://iocwestpac.org/oa/870.html
[13]https://www.oa-africa.net/
[14]http://goa-on.org/regional_hubs/north_america/about/introduction.php
[15]http://goa-on.org/regional_hubs/pitoa/about/introduction.php
[16]https://www.pml.ac.uk/Research/Projects/North_East_Atlantic_hub_of_the_Global_Ocean_Acidif
[17]http://goa-on.org/regional_hubs/mediterranean/about/introduction.php

to have geographically localized coordination that is largely independent of a more global approach.

The GOA-ON Executive Council will continue to ensure representation of the hubs on the global stage and maintain a grassroots approach to the formation and governance of each hub. Beyond this, priorities for the regional hubs from the perspective of the GOA-ON Executive Council include: (1) continued support and capacity building where possible; (2) increased scientific collaboration within and between the hubs; (3) increased sharing of best practices among hubs and between the GOA-ON Executive Council and the hubs; (4) enhanced communication between the hubs and the GOA-ON Executive Council on capacity-building needs and opportunities; and (5) the bottom–up formation of more hubs to create global coverage on a regional scale.

The Latin American Ocean Acidification Network (LAOCA): Status and Vision of the First Hub

LAOCA was the first regional hub formed by GOA-ON members. The LAOCA Network was officially established in December 2015 during the 1st Latin American Workshop on Acidification of the Oceans in Concepcion, Chile. Representatives from Argentina, Brazil, Chile, Colombia, Ecuador, Mexico, and Peru founded the Network. At this first meeting, the members of the LAOCA network stressed the importance of biodiversity in Latin American ecosystems and their willingness to cooperate and to share the information. The first LAOCA Symposium for the members was held in October 2017 in Buenos Aires, Argentina, with the addition of Costa Rica as a new member. This meeting was a unique opportunity to share results about OA observation and research in the region and emphasized the potential of ongoing and future research to address common challenges.

The LAOCA research strategies include:

(i) The study of the carbonate system in coastal, oceanic, and estuarine waters, and its ecological and biogeochemical implications;
(ii) The experimental evaluation of the biological responses of marine organisms to future scenarios of OA and interaction with other climatic and anthropogenic stressors;
(iii) Modeling and projection of local and regional scenarios of OA for Latin America based on monitoring at high spatial and temporal resolution; and
(iv) The effect on socio-ecological systems of the participating countries.

Over the past years, Latin American scientists have identified the need to develop an observing strategy for monitoring fisheries, biodiversity, environmental variability and ecosystem management at their coasts, considering the different levels of observing capacity. Complementary experimental research is needed to improve knowledge about ecosystem and species adaptation potential and the predictive capability of models. Additionally, LAOCA members have identified the need to quantify and improve our understanding of the changes and, in particular, the consequences of OA on ocean and human health, to develop mitigation and adaptation strategies for society. The challenge is to improve communication with stakeholders and help make the best and boldest decisions. One key aspect is advocating the issue of OA on the political agenda for the different countries that take part in the LAOCA network.

At a regional symposium in Santa Marta, Colombia, in March 2018, several priorities were identified that are associated with technical regional standardization, accessibility to equipment and facilities, data and model availability, assertive communication at different levels, and policy relevance and recognition. Common regional data storage and sharing facilities have also been identified as important to foster increased collaboration and harmonization of methods that will increase visibility and best communicate the challenges and implications associated with OA.

The vision for the next 10 years is to facilitate working across the region and expand participation to all countries with coastal zones, convening scientists from different disciplines in order to advance knowledge about OA, its quantification, and its consequences at local and regional levels. LAOCA will continue sharing knowledge through courses to train early-career scientists from the Latin American and Caribbean regions entering the OA field. Finally, LAOCA needs to be a platform to engage with particular stakeholder's needs such as the aquaculture industry, artisanal fisheries or managers seeking environmental solutions.

BROADER INTERGOVERNMENTAL CONSTRUCTS FOR OA ACTION

Like many other environmental problems, OA is a transboundary problem. While the top five countries for CO_2 emissions are China, the United States, India, Russia, and Japan (Janssens-Maenhout et al., 2017), model results show that the Arctic and Antarctic oceans, and the upwelling ocean waters off the west coasts of North America, South America, and Africa are especially vulnerable to OA (Jiang et al., 2015). In other words, the top emitters are not necessarily the countries experiencing the worst effects from OA, which creates a disconnect between actions and impacts.

Many of the countries that will experience the worst impacts of OA are those with limited scientific and technical expertise needed to establish monitoring efforts. Global observing networks such as GOA-ON are key mechanisms to support countries in building scientific capacity. They are also key to provide international organizations, such as IOC-UNESCO, with technical advice to improve the political framework to enable scientific and observational knowledge generation needed to combat the impacts of OA. GOA-ON has been explicitly noted in several intergovernmental fora as an exemplar of international scientific collaboration.

The assessment of international policy and governance options addressing OA has highlighted the fragmented and insufficient political preparedness for mitigating the effects of OA on marine ecosystems and ecosystem services (Herr et al., 2014). Since then, the 2030 Agenda, the UN Framework Convention on

Climate Change (UNFCCC) with its Paris Agreement and the related Marrakesh Global Climate Action Platform on Oceans and Coastal Areas, and the Global Climate Observing System have provided the political rationale to foster and expand OA research and observation through networks like GOA-ON.

Additionally, past developments addressing adaptation to OA have emphasized the need to identify how OA will alter marine life and the ocean economy in the next decade. This will allow the advancement of global and site-specific adaptation strategies and increase the resilience of coastal communities (e.g., Hennige et al., 2014; International Council for the Exploration of the Sea (ICES), 2014). The outcome is expected to feed back into conventions and agreements, such as the Convention on Biological Diversity, the adaptation options within the UNFCCC, and regional fisheries bodies.

Fisheries and Aquaculture, Coral Reef Protection and Tourism, and Other OA-Affected Societal Resources and Their Stakeholders

Ocean acidification effects on many societally relevant issues, like fisheries, aquaculture, coral reef protection and tourism are locally diverse, but need to be globally considered. For example, a globally recognized but localized impact is the plight of Pacific Northwest U.S. shellfish growers who found their natural sets of oysters and their ability to grow shellfish larvae in hatcheries was reduced in the early to mid-2000s (Barton et al., 2015). The combination of coastal upwelling of CO_2-rich waters with the anthropogenic CO_2 uptake tilted aragonite saturation states to low values that impacted the oysters. For now, active monitoring, seawater buffering, and other adaptation practices have alleviated this issue for the hatcheries, but this example serves as a call to action to connect the science to society, especially with respect to OA and fisheries and aquaculture. Globally, the multiple stressors of OA, rising temperatures, hypoxia, and harmful algal blooms will conspire to affect coastal fisheries and aquaculture industries upon which many individuals, cultures, and nations depend. The new Food and Agriculture Organization of the United Nations synthesis volume on "Impacts of climate change on fisheries and aquaculture" outlines impacts, vulnerabilities, and adaptations for marine fisheries in regional seas and focuses on the need for methods and tools for adaptation (Barange et al., 2018). Close collaboration of GOA-ON with fisheries and aquaculture is a critical area for growth and focused attention in the coming decade.

Coral reefs affect coastal economies and ecology in disproportionate ways. While coral reefs cover only 0.16% of the sea surface, they host about 30% of all known marine species and are essential to about 500 million people, generating at least $300–400 billion per year in terms of food and livelihoods from tourism, fisheries, coastal protection and medicines. A recent workshop organized by the Centre Scientifique de Monaco and the IAEA OA-ICC identified nine common solutions for six major coral reef regions and individual localized solutions for each of the diverse reef systems (Hilmi et al., 2018). These examples emphasize the need for a coordinated OA observation network that is relevant to both local and global scales and one that is integrated nimbly across these scales. Local lessons learned and the most efficacious observing strategies to enable adaptation are best shared globally by intentional coordination.

2030 Agenda

Within the UN 2030 Agenda, the aim of SDG 14 is to "conserve and sustainably use the oceans, seas, and marine resources," and consists of 10 targets. GOA-ON supports countries to achieve Target 14.3, which aims to "minimize and address the impacts of OA, including through scientific cooperation at all levels." The progress made toward this target by all UN Member States is measured by the corresponding indicator 14.3.1 "Average marine acidity (pH) measured at agreed suite of representative sampling stations." IOC-UNESCO is the custodian agency for this indicator and was tasked to develop an indicator methodology (Intergovernmental Oceanographic Commission (IOC)-UNESCO, 2018)[18]. GOA-ON provided expert-level input into the methodology, which provides detailed guidance to scientists and countries in terms of what to measure, and how to follow best practice guidelines established by the OA community. It also includes recommendations on how to report and openly share the collected information in a manner that ensures it is transparent, traceable, and useable for global comparison of pH measurements. Through this process, GOA-ON directly contributes to the achievement of SDG Target 14.3. The collective expertise of GOA-ON in science and policy ensures the development of a guiding vision for the collection and sharing of ocean chemistry data, which in the future is envisaged to extend to biological data. The development of the 14.3.1 methodology is the first step in this process.

A streamlined reporting mechanism to obtain a comprehensive OA data set on an annual basis via connecting data providers and different types of data repositories is a main objective of the SDG 14.3.1 methodology. IODE-associated NODCs and Associated Data Units were surveyed in 2018 about the biogeochemical data they hosted, including which of the four carbonate chemistry parameters (pH, TA, DIC, CO_2) they served. More than 50% of these data centers were found to not serve any OA data, which might be due to no active OA observation in the region/country, limited capacity by the respective NODCs to hold this kind of information, or that scientists are directly submitting relevant data to international and/or regional data centers, such as PANGAEA[19] and the Integrated Carbon Observation System[20]. A newly developed 14.3.1 Ocean Acidification Data portal to be launched in 2019 to assist in achieving the full implementation of the 14.3.1 methodology and increasing the capacity of countries to share data.

The 2030 Agenda framework provides many ways to support GOA-ON goal 1 (**Figure 9**). Voluntary Commitments are initiatives undertaken by Governments, the United Nations

[18]See IOC/EC-LI/2 Annex 6 http://unesdoc.unesco.org/images/0026/002651/265127e.pdf.

[19]https://www.pangaea.de/

[20]https://www.icos-ri.eu/

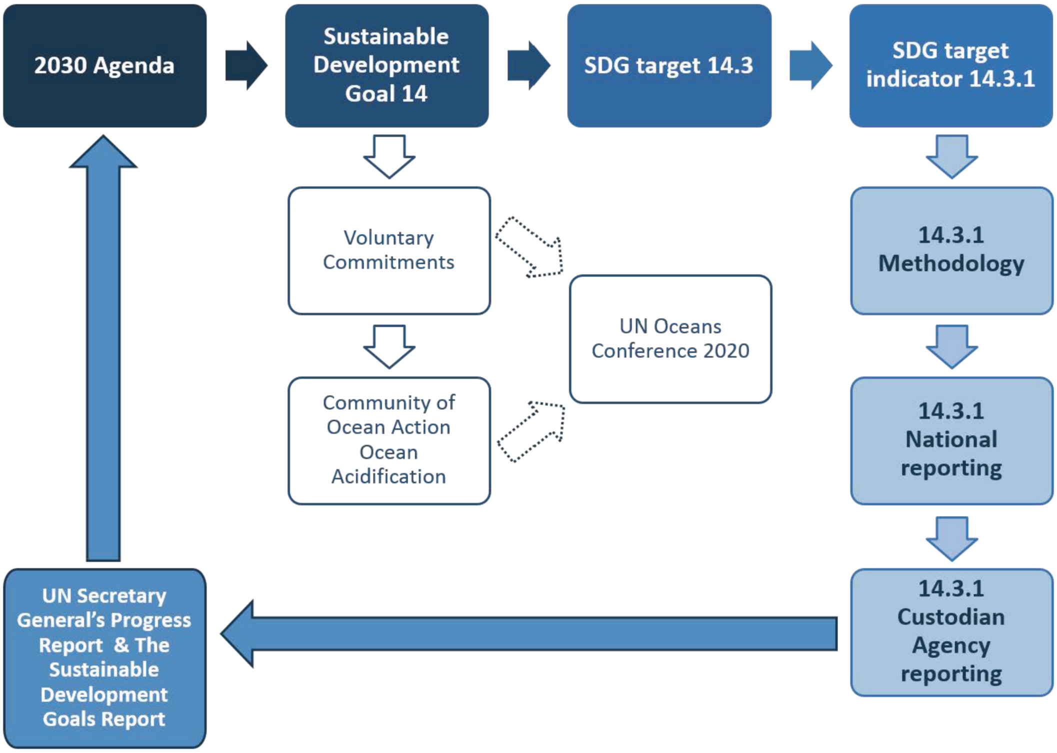

FIGURE 9 | Scheme illustrating the pathways for input to the 2030 Agenda for ocean acidification observations.

system, other intergovernmental organizations, international and regional financial institutions, non-governmental organizations and civil society organizations, academic and research institutions, the scientific community, the private sector, philanthropic organizations and other actors—individually or in partnership—that aim to contribute to the implementation of SDG 14. There are currently 247 Voluntary Commitments that address OA, and 61 are of direct relevance to it. The Voluntary Commitments are organized in a Community of Ocean Action. GOA-ON submitted a Voluntary Commitment (#OceanAction16542)[21], which includes support for measuring OA, storage, and data visualization by 2020. However, these deliverables will only be accomplished with continuous and increasing financial commitment by countries and organizations to establish and sustain OA observations. The UN Ocean Conference 2020 will be the time to assess achievements from Voluntary Commitments and how to proceed.

UN Framework Convention on Climate Change

Ocean acidification gained further recognition through its adoption as a Global Climate Indicator in 2018. The Global Climate Indicators are a suite of seven parameters, presented to the UNFCCC, that describe the changing climate in an effort to recognize impacts beyond temperature change. The Indicators include atmospheric composition, energy, ocean, water and the cryosphere. The inclusion of OA in this list shows the importance of guidance to achieve global alignment in observing OA as provided in the SDG target indicator 14.3.1 methodology.

[21] https://oceanconference.un.org/commitments/?id=16542

CONCLUSION

On a global scale, the building blocks of an integrated OA network in the open ocean are well established and quality-control mechanisms are in place (e.g., Climate and Ocean: Variability, Predictability, and Change [CLIVAR]/GO-SHIP, OceanSITES, SOCONET, SOOP, SOCAT). However, early consensus of the GOA-ON community is that there is a substantial need for increased observation in many coastal areas, particularly in upwelling regions, regions strongly influenced by freshwater, and coral reef environments (Newton et al., 2015). Components of the open ocean system, including the Southern Hemisphere oceans and the polar seas of the Arctic and Antarctic, are poorly sampled and need enhancement through the application of new technology and optimal use of ships and other observing platforms in the region.

For shelf seas and coasts, a global network for assessment of OA is under construction as a high priority for GOA-ON. At the regional level, there are some systems in place with ability to leverage OA observations on existing infrastructure (e.g., World Association of Marine Stations, International Long-Term Ecological Research Network), although many gaps remain. These elements need a globally consistent design, which must also be coordinated and implemented on a regional scale. The Regional Hubs of GOA-ON provide the people-to-people foundation for enhancement of these coastal observations, ensuring that data collected can answer regionally relevant questions.

In the coming decade, the GOA-ON will be a critical resource for meeting the SDG 14.3 target, to "minimize and address the impacts of OA, including through enhanced scientific cooperation at all levels" through expert advice and by facilitating the provision of data to support the associated indicator. Building the capacity of countries to submit data to this indicator will be a guiding priority for the GOA-ON Executive Council in the coming years. By facilitating the collection of data in support of SDG 14.3, GOA-ON contributes to the sustainable use of the ocean envisioned by the 2030 Agenda. In addition, a focus on developing better, more reliable, easy to use, and hopefully lower-cost technologies for data collection of existing and newly vetted parameters, both autonomously and handheld, will support these SDG efforts.

The UN has proclaimed a Decade of Ocean Science for Sustainable Development (2021–2030) to support efforts to reverse the cycle of decline in ocean health and gather ocean stakeholders worldwide behind a common framework, which will ensure ocean science can fully support countries in creating improved conditions for sustainable development of the Ocean. Ocean Science—research and observation—focusing on the impact of multiple stressors on the marine ecosystems, including OA, will be at the heart of the Decade. GOA-ON's activities will be important stepping stones to develop the mitigation and adaptation strategies for sustainable management of ocean resources. Improving the current knowledge on how OA affects ocean economy is essential to predict the consequences of change, design mitigation, and guide adaptation.

Significant progress has been made in the past decade to foster an integrated, leveraged approach to tracking and understanding OA through direct observation. The GOA-ON, a cornerstone of this broader effort, will work to move the community forward to realize this collective vision.

Recommendations

- Coordination among scientists from a range of disciplines (from chemistry to biology to technology development) and from across the globe including developing regions, particularly by:
  - co-locating chemical and biological measurements to build capacity to develop indices, metrics, and risk assessments;
  - articulating needed biological metrics to chemical monitoring programs;
  - collaboratively evaluating the needs and requirements of a global biological monitoring program; and
  - developing a theoretical framework linking chemical changes to biological responses.
- Government, private, and United Nations support for OA observing efforts;
- Develop and enhance regional cohorts working together on regionally specific OA issues;
- Make observational data from the open ocean to coastal to estuarine systems publicly accessible as much as possible;
- Develop capacity so that countries have expertise and guidance needed to report OA data as part of the Sustainable Development Goal 14.3.1 process;
- Promote even closer integration between the Global OA Observing Network and other ocean observing networks focusing on related measurements or issues toward this shared vision;
- Produce observation-based informational products useful for decision making, such as developing tools and mechanisms to visualize the impacts of OA on marine life;
- Optimize the observing system to better support modeling community needs, especially for coastal systems;
- New networks should consider prioritizing the following when considering the future of their OA observing networks:
  - to support monitoring that can contribute to Time of Emergence calculations, some data sets acquired should be from the same location, similar time window, and of "climate quality";
  - to support forecasting and model development, some observations should be prioritized to be real-time or near-real-time;
  - targeted observing initiatives designated for the purpose of characterizing the primary modes of variability that include subsurface observations;
  - co-located physical, chemical, and biological observations to assist in co-stressor and attribution research.
- Encourage research to fill gaps in understanding of the biological, ecological, and socioeconomic impacts of OA, particularly by enhanced research on the impacts and interactions of multiple stressors on marine ecosystems;
- Promote the development of next generation sensor technology, particularly new technology that enhances ability to quantify:
  - the range of natural variability in diverse marine ecosystems; and
  - the organismal response to different biogeochemical conditions;
  - long-term trends in biogeochemical parameters.
- Expand and enhance capacity building efforts to enable broader participation in OA observing and research through:
  - continued growth and support of scientific mentorship activities;
  - further development of regional centers of excellence which can host ongoing trainings and analyze water samples;

- provision of advanced trainings that include lessons on data quality control and quality assurance;
- identification and development of accessible, sustainable data hosting platforms; and
- periodic assessment of global, regional, and local capacity to conduct OA research.

AUTHOR CONTRIBUTIONS

BT, EJ, MD, JH-A, RF, DKG, LH, KI, MK, JN, SS, and FC contributed to the conception and design of the manuscript and provided text that served as the foundation for the manuscript development. BT, EJ, RF, and JN led the review, the design, and the development of the manuscript, with much assistance from ML, SD, DG, ML, MD, EC, and LK. CP, MG, KS, and MT gathered and incorporated larger community input for the manuscript. All authors contributed to the manuscript revision and have read and approved the submitted version.

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REFERENCES

Albright, R., Caldeira, L., Hosfelt, J., Kwiatkowski, L., Maclaren, J. K., Mason, B. M., et al. (2016). Reversal of ocean acidification enhances net coral reef calcification. *Nature* 531, 362–365. doi: 10.1038/nature17155

Arthur, W. B. (2009). *The Nature of Technology: What it is and How it Evolves*. New York, NY: Free Press.

Barange, M., Bahri, T., Beveridge, M., Cochrane, K., Funge-Smith, S., and Poulain, F. (eds) (2018). *Impacts of Climate Change on Fisheries and Aquaculture—Synthesis of Current Knowledge, Adaptation And Mitigation Options*. Rome: FAO.

Barton, A., Waldbusser, G., Feely, R., Weisberg, S., Newton, J., Hales, B., et al. (2015). Impacts of coastal acidification on the pacific northwest shellfish industry and adaptation strategies implemented in response. *Oceanography* 28, 146–159. doi: 10.5670/oceanog.2015.38

Bastviken, D., Sundgren, I., Natchimuthu, S., Reyier, H., and Gålfalk, M. (2015). Technical note: cost-efficient approaches to measure carbon dioxide (CO2) fluxes and concentrations in terrestrial and aquatic environments using mini loggers. *Biogeosciences* 12, 3849–3859. doi: 10.5194/bg-12-3849-2015

Bates, A. E., Helmuth, B., Burrows, M. T., Duncan, M. I., Garrabou, J., Guy-Haim, T., et al. (2018). Biologists ignore ocean weather at their peril. *Nature* 360, 299–301. doi: 10.1038/d41586-018-05869-5

Bauer, J. E., Cai, W. J., Raymond, P. A., Bianchi, T. S., Hopkinson, C. S., and Regnier, P. A. (2013). The changing carbon cycle of the coastal ocean. *Nature* 504, 61–70. doi: 10.1038/nature12857

Bednaršek, N., Feely, R. A., Reum, J. C. P., Peterson, W., Menkel, J., Alin, S. R., et al. (2014). *Limacina helicina* shell dissolution as an indicator of declining habitat suitability due to ocean acidification in the California current ecosystem. *Proc. Roy. Soc. Lond. B* 281:20140123. doi: 10.1098/rspb.2014.0123

Bednaršek, N., Feely, R. A., Tolimieri, N., Hermann, A. J., Siedlecki, S. A., Waldbusser, G. G., et al. (2017). Exposure history determines pteropod vulnerability to ocean acidification along the US West Coast. *Sci. Rep.* 7:4526. doi: 10.1038/s41598-017-03934-z

Bednaršek, N., Harvey, C. J., Kaplan, I. C., Feely, R. A., and Možina, J. (2016). Pteropods on the edge: cumulative effects of ocean acidification, warming, and deoxygenation. *Prog. Oceanogr.* 145, 1–24. doi: 10.1016/j.pocean.2016.04.002

Bittig, H. C., and Körtzinger, A. (2015). Tackling oxygen optode drift: near-surface and in-air oxygen optode measurements on a float provide an accurate in situ reference. *J. Atmos. Ocean. Tech.* 32, 1536–1543. doi: 10.1175/JTECH-D-14-00162.1

Blunden, J., Arndt, D. S., and Hartfield, G. (eds) (2018). State of the climate 2017. *Bull. Amer. Meteor. Soc.* 99, Si–S310. doi: 10.1175/2018BAMSStateoftheClimate.1

Borges, A. V., Alin, S. R., Chavez, F. P., Vlahos, P., Johnson, K. S., Holt, J. T., et al. (2010). "A global sea surface carbon observing system: inorganic and organic carbon dynamics in coastal oceans," in *Proceedings of the OceanObs'09: Sustained Ocean Observations and Information for Society*, eds J. Hall, D. E. Harrison, and D. Stammer (Venice: ESA Publication).

Boyd, P. W., Cornwall, C. E., Davison, A., Doney, S. C., Fourquez, M., Hurd, C. L., et al. (2016). Biological responses to environmental heterogeneity under future ocean conditions. *Global Change Biol.* 22, 2633–2650. doi: 10.1111/gcb.13287

Boyd, P. W., Lennartz, S. T., Glover, D. M., and Doney, S. C. (2015). Biological ramifications of climate-change-mediated oceanic multi-stressors. *Nat. Clim. Change* 5, 71–79. doi: 10.1038/nclimate2441

Breitburg, D. L., Salisbury, J., Bernhard, J. M., Cai, W.-J., Dupont, S., Doney, S. C., et al. (2015). And on top of all that…Coping with ocean acidification in the midst of many stressors. *Oceanography* 28, 48–61. doi: 10.5670/oceanog.2015.31

Bresnahan, P. J., Martz, T. R., Takeshita, Y., Johnson, K. S., and LaShomb, M. (2014). Best practices for autonomous measurement of seawater pH with the honeywell durafet. *Methods Oceanogr.* 9, 44–60. doi: 10.1016/j.mio.2014.08.003

Briggs, E. M., Sandoval, S., Erten, A., Takeshita, Y., Kummel, A. C., and Martz, T. R. (2017). Solid state sensor for simultaneous measurement of total alkalinity and pH of seawater. *ACS Sensors* 2, 1302–1309. doi: 10.1021/acssensors.7b00305

Bushinsky, S., Emerson, S., Riser, S., and Swift, D. (2016). Accurate oxygen measurements on modified Argo floats using in situ air calibration. *Limnol. Oceanogr. Methods* 14, 451–506.

Byrne, R. H., DeGrandpre, M. D., Short, R. T., Martz, T. R., Merlivat, L., McNeil, C., et al. (2010). "Sensors and systems for in situ observations of marine carbon dioxide system variables," in *Proceedings of the OceanObs'09: Sustained Ocean Observations and Information for Society*, eds J. Hall, D. E. Harrison, and D. Stammer (Venice: ESA Publication).

Cai, W.-J., Dai, M., and Wang, Y. (2006). Air-sea exchange of carbon dioxide in ocean margins: a province-based synthesis. *Geophys. Res. Lett.* 33: L12603.

Carter, B. R., Feely, R. A., Mecking, S., Cross, J. N., MacDonald, A. M., Siedlecki, S. A., et al. (2017). Two decades of pacific anthropogenic carbon storage and ocean acidification along global Ocean Ship-based hydrographic investigations program sections P16 and P02. *Global Biogeochem. Cycles* 31, 306–327. doi: 10.1002/2016GB005485

Carter, B. R., Frölicher, T. L., Dunne, J. P., Rodgers, K. B., Slater, R. D., and Sarmiento, J. L. (2016). When can ocean acidification impacts be detected from decadal alkalinity measurements? *Global Biogeochem. Cycles* 30, 595–612. doi: 10.1002/2015GB005308

Chavez, F. P., Pennington, J. T., Michisaki, R. P., Blum, M., Chavez, G. M., Friederich, J., et al. (2017). Climate variability and change: response of a coastal ocean ecosystem. *Oceanography* 30, 128–145. doi: 10.5670/oceanog.2017.429

Chen, C.-T. A., Huang, T.-H., Chen, Y.-C., Bai, Y., He, X., and Kang, Y. (2013). Air-sea exchanges of CO2 in the world's coastal seas. *Biogeosciences* 10, 6509–6544. doi: 10.5194/bg-10-6509-2013

Clarke, J. S., Achterberg, E. P., Connelly, D. P., Schuster, U., and Mowlem, M. (2017). Developments in marine *p*CO2 measurement technology; towards sustained in situ observations. *Trends Analyt. Chem.* 88, 53–61. doi: 10.1016/j.trac.2016.12.008

Clarke, J. S., Achterberg, E. P., Rérolle, V. M. C., Kaed Bey, S., Floquet, C. F. A., and Mowlem, M. (2015). Characterisation and deployment of an immobilised pH sensor spot towards surface ocean pH measurements. *Analyt. Chim. Acta* 897, 69–80. doi: 10.1016/j.aca.2015.09.026

Doney, S. C., Fabry, V. J., Feely, R. A., and Kleypas, J. A. (2009). Ocean acidification: the other CO2 problem. *Annu. Rev. Mar. Sci.* 1, 169–192. doi: 10.1146/annurev.marine.010908.163834

Duarte, C. M., Poiner, I., and Gunn, J. (2018). Perspectives on a global observing system to assess ocean health. *Front. Mar. Sci.* 5:265. doi: 10.3389/fmars.2018.00265

Egea, L. G., Jiménez-Ramos, R., Hernández, I., Bouma, T. J., and Brun, F. G. (2018). Effects of ocean acidification and hydrodynamic conditions on carbon metabolism and dissolved organic carbon (DOC) fluxes in seagrass populations. *PLoS One* 13:e0192402. doi: 10.1371/journal.pone.0192402

Eyre, B. D., Cyronak, T., Drupp, P., Heinen De Carlo, E., Sachs, J. P., and Andersson, A. (2018). Coral reefs will transition to net dissolving before end of century. *Science* 359, 908–911. doi: 10.1126/science.aao1118

Fabricius, K. E., De'ath, G., Noonan, S., and Uthicke, S. (2014). Ecological effects of ocean acidification and habitat complexity on reef-associated macroinvertebrate communities. *Proc. R. Soc. B* 281:20132479. doi: 10.1098/rspb.2013.2479

Fassbender, A. J., Sabine, C. L., and Feifel, K. M. (2015). Consideration of coastal carbonate chemistry in understanding biological calcification. *Geophys. Res. Lett.* 43, 4467–4476. doi: 10.1002/2016GL068860

Feely, R. A., Fabry, V. J., Dickson, A. G., Gattuso, J.-P., Bijma, J., Riebesell, U., et al. (2010). "An international observational network for ocean acidification," in *Proceedings of the OceanObs'09: Sustained Ocean Observations and Information for Society*, eds J. Hall, D. E. Harrison, and D. Stammer (Venice: ESA Publication).

Feely, R. A., Sabine, C. L., Lee, K., Berelson, W., Kleypas, J., Fabry, V. J., et al. (2004). Impact of anthropogenic CO2 on the CaCO3 system in the oceans. *Science* 305, 362–366. doi: 10.1126/science.1097329

Feely, R. A., Wanninkhof, R., Carter, B. R., Landschützer, P., Sutton, A. J., and Triñanes, J. A. (2018). Global ocean carbon cycle. *Bull. Am. Meteorol. Soc.* 99, S96–S100. doi: 10.1175/2018BAMSStateoftheClimate.1

Fennel, K., Alin, S. R., Barbero, L., Evans, W., Bourgeois, T., Cooley, S., et al. (2018). Carbon cycling in the North American coastal ocean: a synthesis. *Biogeosci.* 16, 1281–1304. doi: 10.5194/bg-2018-420

Gattuso, J.-P., Magnan, A., Billé, R., Cheung, W. W. L., Howes, E. L., Joos, F., et al. (2015). Contrasting futures for ocean and society from different anthropogenic CO2 emissions scenarios. *Science* 349:aac4722. doi: 10.1126/science.aac4722

Gruber, N. (2011). Warming up, turning sour, losing breath: ocean biogeochemistry under global change. *Philos. Trans. R. Soc. A* 369, 1980–1996. doi: 10.1098/rsta.2011.0003

Harris, K. E., DeGrandpre, M. D., and Hales, B. (2013). Aragonite saturation state dynamics in a coastal upwelling zone. *Geophys. Res. Lett.* 40, 2720–2725. doi: 10.1002/grl.50460

Harvey, B. P., Agostini, S., Wada, S., Inaba, K., and Hall-Spencer, J. E. (2018). Dissolution: the Achilles' heel of the triton shell in an acidifying ocean. *Front. Mar. Sci.* 5:371. doi: 10.3389/fmars.2018.00371

Hennige, S., Roberts, J., and Williamson, P. (eds) (2014). *An Updated Synthesis of the Impacts of Ocean Acidification on Marine Biodiversity. CBD Technical Series 75*. Montreal, QC: Secretariat of the Convention on Biological Diversity.

Henson, S. A., Beaulieu, C., Ilyina, T., John, J. G., Long, M., Séférian, R., et al. (2017). Rapid emergence of climate change in environmental drivers of marine ecosystems. *Nat. Commun.* 8:14682. doi: 10.1038/ncomms14682

Herr, D., Isensee, K., Harrould-Kolieb, E., and Turley, C. (2014). *Ocean Acidification: International Policy and Governance Options*. Gland: International Union for Conservation of Nature (IUCN).

Hilmi, N., Allemand, D., Claudel-Rusin, A., Gazeau, F., Gaziello, M., Hansson, L., et al. (2018). "From sciences to solutions: ocean acidification impacts on ecosystem services—case studies on coral reefs," in *Proceedings of the Fourth International Workshop on the Economics of Ocean acidification: Bridging the Gap between Ocean Acidification Impacts and Economic Valuation*, (Monaco: Scientific Centre of Monaco).

Hunt, C. W., Snyder, L., Salisbury, J. E., Vandemark, D., and McDowell, W. H. (2017). SIPCO2: a simple, inexpensive surface water *p*CO2 sensor. *Limnol. Oceanogr. Methods* 15, 291–301. doi: 10.1002/lom3.10157

Hunter-Cevera, K. R., Neubert, M. G., Olson, R. J., Solow, A. R., Shalapyonok, A., and Sosik, H. M. (2016). Physiological and ecological drivers of early spring blooms of a coastal phytoplankter. *Science* 354, 326–329. doi: 10.1126/science.aaf8536

Hurd, C. L., Lenton, A., Tilbrook, B., and Boyd, P. W. (2018). Current understanding and challenges for oceans in a higher-CO2 world. *Nat. Clim. Change* 8, 686–694. doi: 10.1038/s41558-018-0211-0

Intergovernmental Oceanographic Commission (IOC)-UNESCO (2012). *A Framework for Ocean Observing By the Task Team for an Integrated Framework for Sustained Ocean Observing (IFSOO)*. Paris: UNESCO.

Intergovernmental Oceanographic Commission (IOC)-UNESCO (2018). *Update on IOC Custodianship Role in Relation. (to)SDG 14 Indicators*. Paris: UNESCO.

Intergovernmental Panel on Climate Change (IPCC) (2013). "Climate change 2013: the physical science basis," in *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, et al. (Cambridge: Cambridge University Press).

International Council for the Exploration of the Sea (ICES) (2014). *Final Report to OSPAR. (of)the Joint OSPAR/ICES Ocean Acidification Study Group (SGOA)*. Copenhagen: ICES.

Janssens-Maenhout, G., Crippa, M., Guizzardi, D., Muntean, M., Schaaf, E., Olivier, J. G. J., et al. (2017). *Fossil CO2 & GHG emissions of all world countries*. JRC Science for Policy Report 107877. Luxembourg: Publications Office of the European Union.

Jiang, L. Q., Feely, R. A., Carter, B. R., Greeley, D. J., Gledhill, D. K., and Arzayus, K. M. (2015). Climatological distribution of aragonite saturation state in the global oceans. *Global Biogeochem. Cycles* 29, 1656–1673. doi: 10.1002/2015gb005198

Johnson, K. S., Plant, J. N., Coletti, L. J., Jannasch, H. W., Sakamoto, C. M., Riser, S. C., et al. (2017). Biogeochemical sensor performance in the SOCCOM profiling float array. *J. Geophys. Res. Oceans* 122, 6416–6436. doi: 10.1002/2017JC012838

Jørgensen, L., Stedmon, C. A., Kragh, T., Markager, S., Middelboe, M., and Søndergaard, M. (2011). Global trends in the fluorescence characteristics and distribution of marine dissolved organic matter. *Mar. Chem.* 126, 139–148. doi: 10.1016/j.marchem.2011.05.002

Karl, T. R., Arguez, A., Huang, B., Lawrimore, J. H., McMahon, J. R., Menne, M. J., et al. (2010). Possible artifacts of data biases in the recent global surface warming hiatus. *Science* 348, 1469–1472. doi: 10.1126/science.aaa5632

Kawaguchi, S., Ishida, A., King, R., Raymond, B., Waller, N., Constable, A., et al. (2013). Risk maps for Antarctic krill under projected southern ocean acidification. *Nat. Clim. Change* 3, 843–847. doi: 10.1038/nclimate1937

Kroecker, K. J., Kordas, R. L., Crim, R., Hendriks, I. E., Ramajo, L., Singh, G. S., et al. (2013). Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. *Global Change Biol.* 19, 1884–1896. doi: 10.1111/gcb.12179

Kwiatkowski, L., and Orr, J. C. (2018). Diverging seasonal extremes for ocean acidification during the twenty-first century. *Nat. Clim. Change* 8, 141–145. doi: 10.1038/s41558-017-0054-0

Laruelle, G. G., Cai, W.-J., Hu, X., Gruber, N., Mackenzie, F. T., and Regnier, P. (2018). Continental shelves as a variable but increasing global sink for atmospheric carbon dioxide. *Nat. Commun.* 9:454. doi: 10.1038/s41467-017-02738-z

Le Quéré, C., Andrew, R. M., Friedlingstein, P., Sitch, S., Pongratz, J., Manning, A. C., et al. (2018). Global carbon budget 2017. *Earth Syst. Sci. Data* 10, 405–448. doi: 10.5194/essd-10-405-2018

Leary, P. R., Woodson, C. B., Squibb, M. E., Denny, M. W., Monismith, S. G., and Micheli, F. (2017). "Internal tide pools" prolong kelp forest hypoxic events. *Limnol. Oceanogr.* 62, 2864–2878. doi: 10.1002/lno.10716

Lenton, A., Tilbrook, B., Law, R., Bakker, D., Doney, S., Gruber, N., et al. (2013). Sea–air CO2 fluxes in the southern ocean for the period 1990–2009. *Biogeosciences* 10, 4037–4054. doi: 10.5194/bg-10-4037-2013

Lindstrom, E. J., Shcherbina, A. Y., Rainville, L., Farrar, J. T., Centurioni, L. R., Dong, S., et al. (2017). Autonomous multi-platform observations during the salinity processes in the upper-ocean regional study. *Oceanography* 30, 38–48. doi: 10.5670/oceanog.2017.218

Marrec, P., Gregori, G., Doglioli, A. M., Dugenne, M., Della Penna, A., Bhairy, N., et al. (2018). Coupling physics and biogeochemistry thanks to high-resolution observations of the phytoplankton community structure in the northwestern Mediterranean Sea. *Biogeosciences* 15, 1579–1606. doi: 10.5194/bg-15-1579-2018

McKinley, G. A., Fay, A. R., Lovenduski, N. S., and Pilcher, D. J. (2017). Natural variability and anthropogenic trends in the ocean carbon sink. *Ann. Rev. Mar. Sci.* 9, 125–150. doi: 10.1146/annurev-marine-010816-060529

McLaughlin, K., Dickson, A., Weisberg, S. B., Coale, K., Elrod, V., Hunter, C., et al. (2017). An evaluation of ISFET sensors for coastal pH monitoring applications. *Reg. Stud. Mar. Sci.* 12, 11–18. doi: 10.1016/j.rsma.2017.02.008

McQuillan, J. S., and Robidart, J. C. (2017). Molecular-biological sensing in aquatic environments: recent developments and emerging capabilities. *Curr. Opin. Biotechnol.* 45, 43–50. doi: 10.1016/j.copbio.2016.11.022

Mignot, A., Ferrari, R., and Claustre, H. (2018). Floats with bio-optical sensors reveal what processes trigger the North Atlantic bloom. *Nat. Commun.* 9, 190–199. doi: 10.1038/s41467-017-02143-6

Miloslavich, P., Bax, N., Simmons, S., Klein, E., Appeltans, W., Aburto-Oropeza, O., et al. (2018). Essential ocean variables for sustained observations of marine biodiversity and ecosystems. *Global Change Biol.* 24, 2416–2433. doi: 10.1111/gcb.14108

Mongin, M., Baird, M. E., Tilbrook, B., Matear, R. J., Lenton, A., Herzfeld, M., et al. (2016). The exposure of the great barrier reef to ocean acidification. *Nat. Commun.* 7:10732. doi: 10.1038/ncomms10732

Muller-Karger, F. E., Miloslavich, P., Bax, N., Simmons, S., Costello, M. J., Pinto, I. S., et al. (2018). Advancing marine biological observations and data requirements of the complementary essential ocean variables (eovs) and essential biodiversity variables (ebvs) frameworks. *Front. Mar. Sci.* 5:211. doi: 10.3389/fmars.2018.00211

Newton, J. A., Feely, R. A., Jewett, E. B., Willamson, P., and Mathis, J. (2013). *Global Ocean Acidification Observing Network: Requirements and Governance Plan, First Edition*. Available at: https://www.pmel.noaa.gov/co2/GOA-ON/GOA-ON_Plan_v1.0_April2014.doc (accessed October 2015).

Newton, J. A., Feely, R. A., Jewett, E. B., Willamson, P., and Mathis, J. (2015). *Global Ocean Acidification Observing Network: Requirements and Governance Plan, Second Edition*. Available at: http://www.goa-on.org/documents/general/GOA-ON_2nd_edition_final.pdf (accessed May, 2019).

Orr, J. C., Fabry, V. J., Aumont, O., Bopp, L., Doney, S. C., Feely, R. A., et al. (2005). Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature* 437, 681–686. doi: 10.1038/nature04095

Palevsky, H. I., and Nicholson, D. P. (2018). The north atlantic biological pump: insights from the ocean observatories initiative irminger sea array. *Oceanography* 31, 42–49. doi: 10.5670/oceanog.2018.108

Rastrick, S. S. P., Graham, H., Azetsu-Scott, K., Calosi, P., Chierici, M., Fransson, A., et al. (2018). Using natural analogues to investigate the effects of climate change and ocean acidification on northern ecosystems. *ICES J. Mar. Sci.* 75, 2299–2311. doi: 10.1093/icesjms/fsy128

Riser, S. C., Swift, D., and Drucker, R. (2018). Profiling floats in SOCCOM: technical capabilities for studying the southern ocean. *J. Geophys. Res. Oceans* 123, 4055–4073. doi: 10.1002/2017JC013419

Sabine, C. L., Feely, R. A., Gruber, N., Key, R. M., Lee, K., Bullister, J. L., et al. (2004). The oceanic sink for anthropogenic CO**2**. *Science* 305, 367–371. doi: 10.1126/science.1097403

Siedlecki, S. A., Kaplan, I. C., Hermann, A. J., Nguyen, T. T., Bond, N. A., Newton, J. A., et al. (2016). Experiments with seasonal forecasts of ocean conditions for the northern region of the california current upwelling system. *Sci. Rep.* 6:27203. doi: 10.1038/srep27203

Spaulding, R. S., DeGrandpre, M. D., Beck, J. C., Hart, R. D., Peterson, B., De Carlo, E. H., et al. (2014). Autonomous in situ measurements of seawater alkalinity. *Environ. Sci. Technol.* 48, 9573–9581. doi: 10.1021/es501615x

Sunday, J. M., Fabricius, K. E., Kroeker, K. J., Anderson, K. M., Brown, N. E., Barry, J. P., et al. (2016). Ocean acidification can mediate biodiversity shifts by changing biogenic habitat. *Nat. Clim. Change* 7, 81–85. doi: 10.1038/nclimate3161

Sutton, A. J., Feely, R. A., Maenner-Jones, S., Musielewicz, S., Osborne, J., Dietrich, C., et al. (2018). Autonomous seawater *p*CO**2** and pH time series from 40 surface buoys and the emergence of anthropogenic trends. *Earth Syst. Sci. Data* 11, 421–439. doi: 10.5194/essd-11-421-2019

Toole, J. M., Krishfield, R. A., Timmermans, M.-L., and Proshutinsky, A. (2011). The Ice-Tethered profiler: argo of the arctic. *Oceanography* 24, 126–135. doi: 10.5670/oceanog.2011.64

Turi, G., Lachkar, Z., Gruber, N., and Munnich, M. (2016). Climatic modulation of recent trends in ocean acidification in the California current system. *Environ. Res. Lett.* 11:014007. doi: 10.1088/1748-9326/11/1/014007

Vargas, C. A., Lagos, N. A., Lardies, M. A., Duarte, C., Manriquez, P. H., Aguilera, V. M., et al. (2017). Species-specific responses to ocean acidification should account for local adaptation and adaptive plasticity. *Nat. Ecol. Evol.* 1:0084. doi: 10.1038/s41559-017-0084

Wang, Z. A., Sonnichsen, F. N., Bradley, A. M., Hoering, H. A., Lanagan, T. M., Chu, S. N., et al. (2015). An in-situ sensor technology for simultaneous spectrophotometric measurements of seawater total dissolved inorganic carbon and pH. *Environ. Sci. Technol.* 49, 4441–4444. doi: 10.1021/es504893n

Williams, N. L., Juranek, L. W., Feely, R. A., Johnson, K. S., Sarmiento, J. L., Talley, L. D., et al. (2017). Calculating surface ocean pCO**2** from biogeochemical argo floats equipped with pH: an uncertainty analysis. *Global Biogeochem. Cycles* 31, 591–604. doi: 10.1002/2016GB005541

Williams, N. L., Juranek, L. W., Feely, R. A., Russell, J. L., Johnson, K. S., and Hales, B. (2018). Assessment of the carbonate chemistry seasonal cycles in the southern ocean from persistent observational platforms. *J. Geophys. Res.* 123, 4833–4852. doi: 10.1029/2017JC012917

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REVIEW
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The Importance of Connected Ocean Monitoring Knowledge Systems and Communities

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Ocean monitoring will improve outcomes if ways of knowing and priorities from a range of interest groups are successfully integrated. Coastal Indigenous communities hold unique knowledge of the ocean gathered through many generations of inter-dependent living with marine ecosystems. Experiences and observations from living within that system have generated ongoing local and traditional ecological knowledge (LEK and TEK) and Indigenous knowledge (IK) upon which localized sustainable management strategies have been based. Consequently, a comprehensive approach to ocean monitoring should connect academic practices ("science") and local community and Indigenous practices, encompassing "TEK, LEK, and IK." This paper recommends research approaches and methods for connecting scientists, local communities, and IK holders and their respective knowledge systems, and priorities, to help improve marine ecosystem management. Case studies from Canada and New Zealand (NZ) highlight the emerging recognition of IK systems in natural resource management, policy and economic development. The in-depth case studies from Ocean Networks Canada (ONC) and the new Moana Project, NZ highlight real-world experiences connecting IK with scientific monitoring programs. Trial-tested recommendations for successful collaboration include practices for two-way knowledge sharing between scientists and communities, co-development of funding proposals, project plans and educational resources, mutually agreed installation of monitoring equipment, and ongoing sharing of data and research results. We recommend that future ocean monitoring research be conducted using cross-cultural and/or transdisciplinary approaches. Vast oceans and relatively limited monitoring data coupled with the urgency of a changing climate emphasize the need for all eyes possible providing new data and insights. Community members and ocean monitoring scientists in joint research teams are essential for increasing ocean information using diverse methods compared with previous scientific research. Research partnerships can also ensure impactful outcomes through improved understanding of community needs and priorities.

Keywords: Indigenous knowledge, ocean monitoring, Ocean Networks Canada, mātauranga Māori, Inuit Nunangat, Whakatōhea, traditional ecological knowledge, socio-ecological systems

INTRODUCTION

For ocean monitoring to result in improved outcomes for human and ecological systems, both must be accounted for, together. This is particularly true in places where connections to ecosystem productivity remain direct, visible, and integrated socially, culturally and ecologically with coastal communities (Chaturvedi, 2016). However, a comprehensive approach to ocean monitoring that includes local and traditional ecological knowledge (LEK and TEK), and Indigenous knowledge (IK) (Lessard et al., 2002; Clark et al., 2010; Addison et al., 2018) requires costly investments in time and resources (Danovaro et al., 2016). Monitoring investment decisions are generally based on current knowledge, knowledge gaps, and interests across a wide range of both ecosystem services and interest groups (Patrício et al., 2016). These groups range from local to global and may include Indigenous communities. The scale at which ocean monitoring investment decisions are made therefore often varies. When funding and/or scientific inquiry leading to changes in ocean monitoring comes from regional or global interests, successful mechanisms for maintaining local and Indigenous relationships to the systems must be put in place to fully and equitably engage the local and Indigenous communities (Proctor et al., 2010).

Where Indigenous communities form part or all of the socio-ecological system in particular, the socio-ecological system conditions, and their vulnerabilities, are spatially and institutionally dependent (Berkes, 2009). Therefore, one-size-fits-all methods are unlikely to ensure localized ecosystem and cultural integrity (Berkes, 2009). In these cases, Indigenous communities play a very important role in understanding and sustaining the ecosystems to which they belong. Indigenous communities provide knowledge that helps create appropriate management strategies for a given locality (DeFries et al., 2005). However, given the rapidly changing climate, scientific, local, and Indigenous monitoring can complement each other and greatly assist co-management of marine species harvests, including seaweeds by locals and Indigenous communities (Moller et al., 2004) and arctic char fishing in the Canadian Arctic.

In this paper, we refer to monitoring practices rooted in the academic, scientific tradition as "science" and practices which have emerged through Indigenous communities' long histories of practice in managing local resources as "Indigenous knowledge (IK)." These have often been described as TEK, LEK, and other methods. Citizen science, where the non-academic community participates in data collection creating citizen-based observations which then need to be standardized and made compatible with other datasets, sits within the IK-Science spectrum (Busch et al., 2016). We recognize that these systems of knowledge are not mutually exclusive. Indeed, the focus of this paper is to explore how methods in these systems can complement each other in developing a more complete approach to ecosystem management and ecological knowledge.

Connecting IK and science enables Indigenous marine system participants to evaluate scientific predictions using their own forms of adaptive management; these can include "learning by doing" (Walters and Holling, 1990), creating a general community consensus (Berkes et al., 2000), and adaptive harvesting according to seasonal indicators based on oral traditions and community knowledge. Scientific and Indigenous monitoring methods complement each other because they can operate efficiently at different scales and with different foci, both of which are needed for improved decision-making and environmental and resource governance.

Science can provide a precise and quantitative evaluation of marine conditions and expectations, and address larger spatial scales, e.g., using remote sensing. Science-based observing provides a methodology for systematic coverage of larger study areas which include locations where no harvesting – or harvesting by interests outside of the socio-ecological system – occurs, or where Indigenous monitoring and information exchange intensity is likely to be lower and/or more diffuse. These methods can determine how and why a certain species or ecosystem is changing/fluctuating, but they can be expensive and can miss key ecosystem interactions that are already understood at local scales.

Monitoring based on IK fills in other gaps which science cannot. Indigenous methods are typically qualitative, and relatively inexpensive as the costs are shared with direct participation in the culture and use of the marine resources. Indigenous methods are rapid, can incorporate large sample sizes of harvested resources (as opposed to temporally or spatially limited scientific field samples), are based on centuries long time period observations, and enable the local participants to engage directly in the ecosystem's sustainability and protection (Moller et al., 2004). This is the case, for example, when the observations depend on specialized knowledge of the observer such as a hunter's knowledge of species migration or knowledge of safe alternative travel routes over ice. If this knowledge has been gained through experience or shared traditions, then subtle observations of changes to migration routes or reacting to varying weather patterns is best done by the holder of this knowledge and may not be easily captured through science.

Furthermore, Indigenous monitoring can generate reports of unusual events and occurrences instead of average patterns. For instance, Indigenous communities in the Arctic have observed increases in frequency of extreme and less predictable weather events, which is a sign of long-term ecosystem alteration (Krupnik and Jolly, 2002). The Local Environmental Observer (LEO) network is an example of documenting these observations through an on-line, map-based internet portal in which users can upload unusual climate-related environmental observations (Alaska Native Tribal Health Consortium [ANTHC], 2018). In a large geographical area where detailed data are needed, having a large number of knowledgeable observers, the "many eyes" approach (Dickinson et al., 2012), is an effective way of finding rare organisms, tracking changes in species presence or abundance, tracking boom and bust cycles, among other ecologically relevant discoveries.

Communities can provide a better understanding of underlying patterns and can test the tools that can reduce monitoring costs and improve outcomes in marine systems. These tools may include co-management and collaborative management generated specifically for the socio-ecological systems and institutional frameworks of the Indigenous communities and stakeholders, maintaining their vital roles in understanding marine ecosystem values and the risks they face in the next decade and beyond. However, it can be difficult for researchers and harvesters to work together, as resource dependent and Indigenous communities do not always trust scientists or their methods (Moller et al., 2009). Nonetheless, consistent scientific monitoring could improve predictions and signal if, for example, a population will be, or is, overharvested, or at risk from a forecasted environmental event, such as a marine heat wave, prompting resource users to adapt and change their methods and strategies to assure resource sustainability.

Changes in monitoring capabilities currently underway are dramatically lowering technical and information costs, through, e.g., requirements for ships to have working Automatic Identification Systems (AIS) and the rapid expansion and implementation of Unmanned Aerial Vehicles (UAV) across multiple scales (e.g., note the Commercial UAV Show has grown to include over 3000 attendees from over 60 countries in 5 years[1]), as well as real-time satellite imagery and response opportunities (Dunn et al., 2018). While these are increasing prospects for widespread ocean monitoring, including in remote areas, and focusing discussion on "the Essential Ocean Variables (EOVs)" for sustainability (Miloslavich et al., 2018a), these valuable efforts lack inclusion of TEK, LEK, IK and Indigenous communities, and will omit some types of observations dependent on specialized knowledge or "many eyes" as described above.

Coming changes in underlying benefits and costs of spatially and institutionally dependent ocean productivities will change how monitoring investments return benefits to communities. These changes must be anticipated in any integrated scientific and Indigenous framework that aims to include how knowledge from monitoring is to be acquired, taken up, acted upon, and used going forward. To accomplish this, Indigenous communities must be actively and comprehensively included in the research and governance processes as more than either contributors of TEK or IK, or recipients of, e.g., conservation mandates. Local and Indigenous communities must maintain at least joint decision-making power of the new knowledge produced. This is particularly important in regions where Indigenous territorial rights and governing autonomy are increasingly recognized, such as in the Canadian and NZ contexts. This paper investigates case studies in Indigenous communities of Canada and NZ to better understand how decisions regarding ocean monitoring are interlinked with the well-being of community members. We explore underlying patterns regarding the emerging power of IK systems, especially in influencing natural resource management, policy, and economic development in these particular contexts.

Success or failure of monitoring investments will depend on the extent to which they can facilitate improvements in the socio-ecological systems. An example of recent success is the Arctic Marine Pulses Model, which works to align "spatially focused and time-deep" IK with "spatially broad and time-shallow" conventional science through commonalities grounded in seasonal cycles rather than attempting to force a "one-to-one correspondence between biophysical event and subsistence activity" (Moore et al., 2018). Both scientists and Indigenous hunters provide inputs into the shared framework and both gain from the increased information because the research and IK co-exist on a common spatio-temporal scale that is "recognizably meaningful" to both groups (Moore et al., 2018).

This highlights the importance of considering how benefits and costs of increased monitoring of ocean conditions vary amongst different interest groups, and whether there are useful dimensions through which to fully or partially align them. As Indigenous communities redevelop their economic base and resource control, opportunities may emerge to co-invest which may also improve power relationships. In particular, we will emphasize expected issues regarding ocean monitoring of human behavior, and the joint determination, and feedback effects, of how we choose what and where to invest in monitoring across various scales, and the human behaviors and potential outcomes for well-being.

Our discussion focuses on resource use and governance systems for existing natural resource stocks, and for cases where resources may be enhanced by human interventions such as aquaculture. Systems may be susceptible to ecological and/or social changes occurring in space and time as well as across layers of knowledge and distributions of benefits from ecosystems' many services. Investments in knowing more, through monitoring, then become a response to these susceptibilities that target different spatial, temporal, informational and distributional scales accordingly. A comprehensive approach to the future of ocean resource use and monitoring presents improved opportunities for understanding changes in the ecosystem, whether induced by direct or indirect human actions. Ocean monitoring investments represent a policy intervention to be applied at large scale, technological monitoring systems, and also at multiple points in the process of change, beginning with the determination of baseline conditions and continuing through efforts to prevent, contain, control, mitigate, or adapt to negative consequences of change.

SETTING THE STAGE: LOCAL AND INDIGENOUS COMMUNITIES IN OCEAN MONITORING

Indigenous communities are widely engaged in ocean monitoring that affects their well-being. Before discussing cases from Canada and NZ in depth, we briefly consider an example that illustrates some of the complexities involved; in particular, we consider the role of body condition of a hunted resource as a focus for monitoring efforts. This example also illustrates how science and IK can cooperate in monitoring, subject to careful consideration of introduced biases or interconnected ecosystem impacts.

Each autumn Rakiura Māori travel across 35 islands surrounding Stewart Island, to harvest sooty shearwater (*Puffinus griseus*), also called *tītī* (Moller et al., 2004) at the southern end of NZ. These events are important for Rakiura Māori for the

[1]www.terrapinn.com/exhibition/the-commercial-uav-show

earnings gained by selling *tītī*, and as part of their cultural identity and cultural well-being (Lyver et al., 1999; Kitson, 2004). Written records of harvest rates, weather, and hunt times are kept (Moller et al., 2004, 2009). *Tītī* gatherers have been able to monitor *tītī* well-being over the long-term using catch rates. By observing yearly fluctuations in catch rate, they concluded, for example, that body condition, harvest intensity and breeding habitat in Rakiura, NZ depended on outside factors that influenced the population during migration (Lyver, 2002). Rakiura Māori base their short-term catch on "touch, feel, and sight," as they determine *tītī* presence or absence by smell and sound (Newman and Moller, 2005). Body condition is used as a population health indicator, where fat represents health; i.e., the fatter the animal, the healthier the animal (Kofinas et al., 2004). However, high body condition can only be an indicator of population well-being if body condition is independent from population density. In fact, body condition depends on population density; hence, a high body condition can represent overharvesting or overgrazing, which could lead to a drastic decrease in population if nothing is done (Moller et al., 2004).

Human and ecological conditions are susceptible to change. The desire to establish global baselines and monitoring capabilities is increasing. Miloslavich et al. (2018a) use a Drivers-Pressures-State-Impact-Response (DPSIR) model to capture important global ocean trends and identify EOVs that should be monitored over time. This is part of a young but growing literature setting the stage for monitoring demands, and therefore investment priorities, over the coming decade (Pereira et al., 2013; Bax et al., 2018; Chiba et al., 2018; Crise et al., 2018; Miloslavich et al., 2018a,b; Moore and Reeves, 2018; Muller-Karger et al., 2018).

Bax et al. (2018) reference an older literature that stressed how sustained observing "requires a coordinated, collaborative and culturally appropriate process, incorporating Indigenous and local knowledge, with long-term resourcing that meets identified local, national, and regional needs." This framework resulted in the development of ocean monitoring focused on project-based needs rather than a more broadly strategic global initiative. This has resulted in limited applicability to broader audiences. A positive initial focus on capacity development may subsequently be devolving into a linear progression from large-scale scientific data being packaged and distributed as information to end-users instead of co-producers and collaborators.

A further concern relates to the ways in which research publication outlets may mask important lessons from project-based research. That is, there is some indication that the scientific literature may perpetuate conventional science at the expense of more collaborative and inclusive efforts. Miloslavich et al. (2018a), in developing their DPSIR model, drew on thousands of papers in the SCOPUS database, and 100+ biological ocean observing programs since the dawn of the 20th century, but mainly after the 1970s, to source their findings regarding EOVs. There is no mention, however, of Indigenous communities or traditional knowledge (TK) holders as continuous sources of TEK stretching back many generations. Drawing on SCOPUS to measure the scientifically relevant and societal impact of potential EOVs may exacerbate exclusions of IK and communities.

Of the remaining recent articles on emerging EOVs identified above, only Chiba et al. (2018) and Moore and Reeves (2018) make any mention of Indigenous communities. Chiba et al. (2018) simply identify 2020 AICHI Target 14, which aims to monitor and protect "ecosystems that [. . .] take into account the needs of Indigenous and Local communities" among other needs, as still lacking a marine relevant specific indicator.

This may initially appear to be a small-scale concern given the marginal status of many marine and coastal Indigenous stakeholders (Gutiérrez et al., 2011). However, there are approximately 370 million Indigenous people, from 5000 groups, in 90 countries around the world[2]. Globally, small scale fisheries employ about 90% of fishers worldwide and about 50% of fish consumed by humans (Le Cornu et al., 2018). Living ocean resources are at the same time becoming scarcer, which pushes fishers and harvesters to overharvest in order to meet growing demand (Auriemma et al., 2014). As a result, Costello et al. (2012) show in their study that 64% of small-scale fisheries are suffering from overfishing consequences, endangering food security for hundreds of millions of people. In Pacific Island countries, over 1/4 of households engage directly in fishing activities and current fish consumption can be as high as 110 kg/person/year. Local fish shortages resulting in significant food insecurity are predicted to occur within the next two decades (James et al., 2018). Management strategies to avoid overfishing must be employed globally and still be able to adapt to independent local fishery and community needs.

In addition, aquaculture is increasingly being turned to as a way to increase marine resource bases and increase food security. This is, however, generating a new and complex set of concerns, including marine environmental pollution that requires monitoring and understanding (Pelletier et al., 2018).

Fisheries are also an important resource for economic transitions from non-market to market activities. In Greenland, for example, where 90% of the population is Indigenous Inuit, about 90% of its Gross Domestic Product (GDP) is generated from fishing[3]. Furthermore, a significant portion of the food supply comes from subsistence fishing and hunting (eds. Glomsrød et al., 2017). Revenues from small-scale Pacific Island fisheries, even when fragmented, poorly managed and greatly undervalued in GDP statistics (Zeller et al., 2006), are significant contributors to local communities, with the potential to reach billions of dollars in value if they enter global supply chains through a more market-driven focus (Dunn et al., 2018; Le Cornu et al., 2018).

The changing demands for ocean resources through potential overharvesting and increased breadth and marketization of ecosystem uses in fisheries and aquaculture argue for building strong connections with scientific, local and Indigenous monitoring; successful monitoring efforts will be context specific, will include connecting resource uses across scales and community interests, and will generate participant

[2] www.culturalsurvival.org

[3] http://www.stat.gl/ (accessed March 10, 2019).

buy-in through a combination of actionable results and specific understanding.

It is essential that information from successful projects be integrated into the development of monitoring tools and EOVs at every scale, so that the "learning, designing, and managing" (Le Cornu et al., 2018) needed to improve local and Indigenous livelihoods, far from globalized trade and information routes, can evolve. The case studies presented here support this need by drawing together multiple project results from distinct Indigenous communities to re-assert the primacy of socio-ecological systems in the co-production of knowledge in the rapidly emerging technology-driven progress in ocean observing.

CASE STUDIES

NZ Case Study

NZ Cultural Context

The principles and history of the Treaty of Waitangi 1840 (the Treaty) are fundamental to understanding Māori-Crown relationships in NZ. Māori are the Indigenous peoples of NZ; there are over 100 Iwi (tribes) and over 800 Hapū (sub-tribes)[4]. From the late 1700s European settlers came to NZ, and desired a government. In 1840, >500 Māori leaders signed the Treaty of Waitangi with British Crown representatives, who went on to form the government. The Treaty was written in English and Te Reo Māori (the Māori language), with the Te Reo Māori version assuring Māori would retain rangatiratanga (sovereignty) over land, forests, fisheries and prized possessions, while the English version said that Māori would cede sovereignty. This caused rights and sovereignty disputes between parties. The Treaty principles are: partnership, participation, and protection. The Crown breached these principles numerous times, and created a history of mistrust. However, NZ is now in an era of grievance settlement. Treaty principles are recognized throughout government policy and legislation, including Treaty grievance settlement legislation (Hepi et al., 2018). These changes are encouraging Crown agents, including Crown funded researchers and research institutions, to over overcome the historical mistrust and build strong, positive relationships with Māori to ensure public confidence in their work (Māori Policy Unit., 2011).

Since 2005, the Vision Mātauranga (VM) policy has provided strategic direction on how Māori people, resources and mātauranga (knowledge) can help to create a healthier, more vibrant and sustainable NZ, through government-funded research (Ministry of Science Research and Technology, 2005). This includes investing in Māori-relevant research, developing Māori research capability, fostering connections between Māori, government, the science system, and industry; and supporting Māori community-led research and development strategies. Since 2015, VM has been integrated across the government science investments, which has motivated researchers to improve their engagement with Māori communities (Local Government New Zealand, 2007, 2011).

Cross-Cultural Research in NZ

The extensive interactions of Māori with the natural world have contributed to a comprehensive body of knowledge, often referred to as mātauranga Māori (Harmsworth and Awatere, 2013; Hikuroa, 2017; Jackson et al., 2017). Mātauranga Māori exists, is understood and is applied at various levels, i.e., by Māori across NZ, at Iwi, Hapū and whānau (family) levels. Mātauranga Māori also includes processes for gaining, managing, applying, and transferring knowledge (Robb et al., 2015). Smith (2012) defined kaupapa Māori research principles that help to focus what "good" research might be like for Māori. These principles include:

- Tino rangatiratanga (self-determination),
- Taonga tuku iho (cultural aspiration),
- Ako Māori (culturally preferred pedagogy),
- Kia piki ake i ngā raru o te kainga (socio-economic mediation),
- Whānau (extended family structure),
- Kaupapa (collective philosophy),
- Te Tiriti o Waitangi (The Treaty of Waitangi), and
- Ata (growing respectful relationships).[5]

Cross-cultural research allows a broader set of knowledge systems, principles, and non-Māori to participate in research, with kaupapa-Māori research remaining an important part of the bigger research picture. Cross-cultural research takes place across or between cultures, including research undertaken by non-Indigenous researchers into the lives of Indigenous people or by Indigenous people working from within western frameworks, with their own people (Gibbs, 2001). Hardy et al. (2015) consider cross-cultural research to be possibly one of the most difficult areas of research, with the cultural and institutional setting of the research, and the personalities involved, determining which methods are most appropriate.

In collaborative research, research participants and researchers are equal partners in the research process, and all parties benefit from the research (Gibbs, 2001). Transdisciplinary collaborations work across different knowledge systems and cultures, and include collaborative discussions between researchers, interest groups and community representatives (e.g., natural resource managers, policy-makers, local, and Indigenous communities) (Ogilvie et al., 2018). Hepi et al. (2018) provides a NZ marine example where cross-cultural research practices were used by Environmental Science Research (the research provider), Te Uri o Hau (the Iwi), and Integrated Kaipara Harbour Management Group (the management collective), jointly setting the research agenda, collecting, and analyzing the data. They commonly seek to establish priorities and then foster research that helps different parties move toward commonly sought outcomes, while creating new knowledge and understanding.

Hardy et al. (2015) draws on two case studies from the North Island, NZ (Tauranga Harbour and Horowhenua coastline) to provide real examples of cross-cultural research processes, principles, and methods. Success factors for

[4]http://www.tkm.govt.nz/ (accessed November 15, 2018).

[5]For more on these principles visit http://www.rangahau.co.nz/research-idea/27/.

cross-cultural environmental research identified in the authors' experiences were:

- That the research itself is meaningful and beneficial to Indigenous people and local communities and goes beyond outputs and outcomes;
- To agree on a shared research vision/purpose, and research objectives, and genuine will to be collaborative are vital;
- Respect and space for different knowledge systems need to be practiced not just preached;
- Methodological pluralism must occur;
- "Knowledge integration" (except where appropriate) and "knowledge imperialism" need to be resisted;
- Building capacity on both sides is vital to understanding each other's perspectives and knowledge bases;
- Honesty and communication are what build trust and long-term relationships; and
- Shared space for understanding and sharing from different knowledge systems, i.e., science and Indigenous, should be built into the research design.

Importance of the Marine Environment to Māori

Rout et al. (2018) characterize seafood as the most important part of the Māori marine economy (**Figure 1**). Historically Māori were significant fishers and traders in seafood although the first fisheries legislation, the Oyster Fisheries Act 1866, excluded Māori, despite clear evidence that Māori had been major oyster traders. Fisheries legislation contained provisions supposedly protecting the fisheries guaranteed to Māori under the Treaty, but these protections were ineffective (Tau, 2006). Today Māori again hold significant rights in fisheries and aquaculture due to the Māori Fisheries Settlement process, which began in the 1990s, and Māori Aquaculture Settlement process, which began in the 2000s.

The seafood sector brings \$4.18B to NZ annually. It is managed through recreational, customary, and commercial fisheries, and aquaculture. Māori own 1/3 of the NZ aquaculture industry, and >50% of the NZ commercial fishery. Māori represent a large part of the recreational fishery and are sole participants in the customary fishery. Moana New Zealand is the largest Māori-owned seafood company that arose through the Māori Fisheries Settlement. The Māori worldview is increasingly informing how Māori commercial fishing operates, with increasing effort on sustainability[6]. NZ has the 10th longest coastline of countries globally, and successful aquaculture operations for mussels, salmon and oysters under both Māori and non-Māori owned companies.

In addition to Māori seafood sector interests, and more importantly, is Māori ability to exercise cultural practices that reflect values, such as kaitiakitanga. Kaitiakitanga is a reciprocal responsibility of care between Māori and their affiliated place. The term "tiaki" includes notions of guardianship, care and wise management. Kaitiakitanga transcends across the spiritual, intellectual and physical planes, recognizing that physical damage to a resource also results in spiritual damage and an intellectual loss. Failure to recognize all elements of a resource results in a loss of mauri (life force). Upholding mauri is directly connected to the mana (prestige, authority) and rangatiratanga (sovereignty) of the local Māori people, and is therefore vital to positive Māori well-being (Tawharau o nga Hapū o Whakatohea Iwi Management Plan, 1993). Māori will be better able to exercise tīkanga and kaitiakitanga over their rohe moana (ocean territories) by sharing ocean mātauranga, participating in ocean monitoring, and also by responding to the information provided by the ocean monitoring through managing their marine ecosystem activities, e.g., fishing, aquaculture, boating.

The Moana Project

The Moana Project[7] aims to revolutionize ocean forecasting to underpin NZ's blue economy. The project spans multiple sectors and interests, and it includes representatives from Iwi, Māori academics, the ocean observing and modeling community, and seafood sector. While only in early stages, the project provides an example for coastal Indigenous communities with marine sector aspirations globally.

Using transdisciplinary methods from kaupapa-Māori research, social sciences and novel ocean observing and modeling technologies, an ocean-knowledge exchange platform will be developed that supports marine spatial planning and impact assessments to inform Iwi governance of multi-sector activities in their rohe moana (territorial sea). Embracing Internet of Things concepts, we are developing low-cost temperature sensors that can be deployed on all boats, at all times, by anyone. The data will feed back into our ocean modeling platforms, providing optimized ocean forecasts to the community more broadly, thereby completing the circle from data collection to informed decision making.

A case study with Bay of Plenty Iwi, Whakatōhea (**Figure 2**), demonstrates an exchange of oceanographic knowledge across Indigenous and science communities. Alongside their customary fisheries and cultural interests, i.e., kaitiakitanga, Whakatōhea has specific commercial interests in fisheries and aquaculture. Whakatōhea has four seafood entities: Whakatōhea Fisheries Asset Holding Company, Pākihi Trading Company Limited, Whakatōhea Mussels Ōpōtiki Ltd., and Eastern Seafarms Ltd. Whakatōhea has been researching offshore mussel farming since 2010, and has interests in a 3800 ha mussel farm with a further 5000 ha proposed through a Treaty settlement, which would create the largest offshore aquaculture area in the world. The Moana project will also support regional growth aspirations, such as creating 350+ aquaculture-related jobs by 2023.

Ocean Networks Canada Case Study: A Project on Changing Sea Ice

Ocean Networks Canada (ONC), a Canadian national not-for-profit society, operates and manages innovative cabled observatories on behalf of the University of Victoria. These observatories supply continuous power and Internet connectivity to various scientific instruments located in coastal, deep-ocean, and Arctic environments. ONC's cable arrays host

[6] See www.moana.co.nz/ responsibility for Moana New Zealand's sustainability journey.

[7] www.moanaproject.org

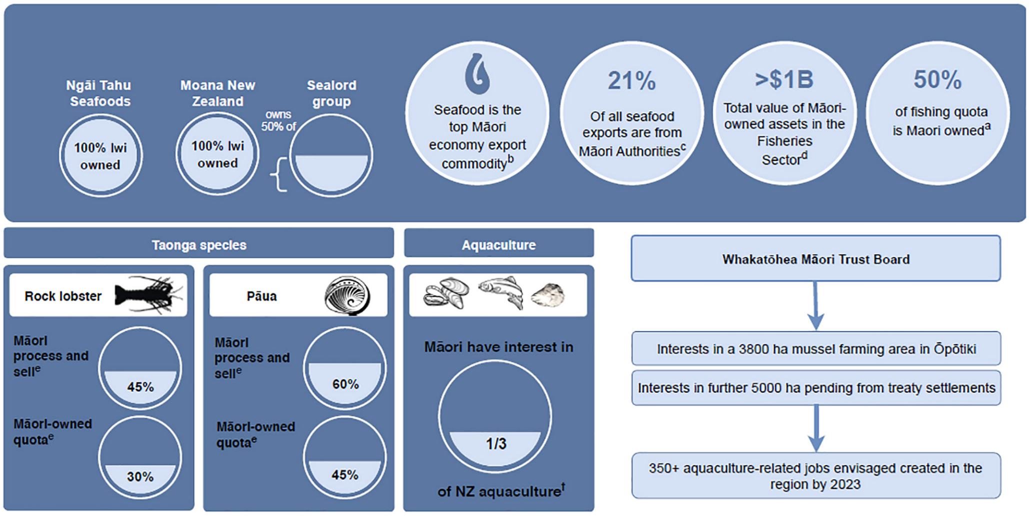

FIGURE 1 | The economic benefit of fisheries and aquaculture to Māori, including Whakatōhea Māori Trust Board. [a]Inns (2013). [b]NZ Government Business Growth Agenda. [c]Joseph (2017). [d]Nana et al. (2011). [e]McClurg (personal communication). [f]NZ Aquaculture (personal communication).

hundreds of sensors distributed in, on and above the seabed, along with mobile and land-based assets. In addition to fixed observatories, ONC is developing a national network of community-based monitoring programs with data collection performed by community members (**Figure 3**).

Ocean Networks Canada uses an approach where local residents in communities, academic scientists, and government staff collaborate in projects that benefit all parties. For any monitoring activity taking place in communities, ONC seeks involvement and feedback from local communities throughout the lifetime of the project, from conception to proposal, planning, and implementation. The community-based approach enhances instrument-based and remote sensing programs by directly incorporating IK.

Data from these efforts are complemented by IK; monitoring locations and programs are informed by priorities in coastal communities. Data are made freely available over the Internet, on local data displays, and disseminated directly in communities through meetings and face-to-face communication. The information is used by a wide variety of stakeholders, including community members, scientists, teachers, students, researchers, community leaders, government staff, and industry in Canada, and around the world.

Canadian Cultural Context

There are approximately 65,000 Inuit in Canada, the majority of whom live in four northern regions: the Inuvialuit Settlement Region (Northwest Territories), Nunavut Territory, Nunavik (Northern Québec), and Nunatsiavut (Northern Labrador). Collectively, these four regions make up Inuit Nunangat, the Inuit homeland in Canada. This vast area includes 53 communities and encompasses roughly 35% of Canada's landmass and 50% of its coastline (Inuit Tapiriit Kanatami [ITK], 2018). Compared with the current overall Canadian population of just over 37,000,000 (Statistics Canada, 2018), geographically speaking, the Inuit have a proportionately large responsibility and interest in the coastal environment.

The Inuit Tapiriit Kanatami (ITK) is the national representational organization for the Inuit. In 2018, the ITK published the "National Inuit Strategy on Research," a comprehensive document which outlines recommendations and practices which respect Inuit self-determination in Inuit Nunangat research (Inuit Tapiriit Kanatami [ITK], 2018). The Strategy is based on the premise that public policies, informed by the best available evidence derived from both Inuit knowledge and western science will support optimal decision-making for Inuit, and in turn will bring benefit to all Canadians.

Research in Inuit Nunangat by and large has excluded Inuit as equal participants, resulting in research that is resourced and conducted in a way that has limited Inuit participation. Rather than including Inuit expertise as a core source of knowledge, environmental research was (and in some cases, continues to be) conducted by researchers with little connection or respect for the deep experience of the residents and caretakers of Inuit Nunangat.

Within the broad goal of creating social and economic equity, and in the context of ongoing reconciliation with Indigenous peoples in Canada, the Strategy outlines five critical areas for action which will lead to an equitable and mutually beneficial relationship between all research participants in Inuit Nunangat: (1) Advance Inuit governance in research; (2) Enhance the ethical conduct of research; (3) Align funding with Inuit research priorities; (4) Ensure Inuit access, ownership, and control over data and information; and (5) Build capacity in Inuit Nunangat research.

Some areas of collaboration specific to environmental research and monitoring include ensuring that Inuit:

- Are partners in setting the research agenda,
- Actively participate in all aspects of the research, and

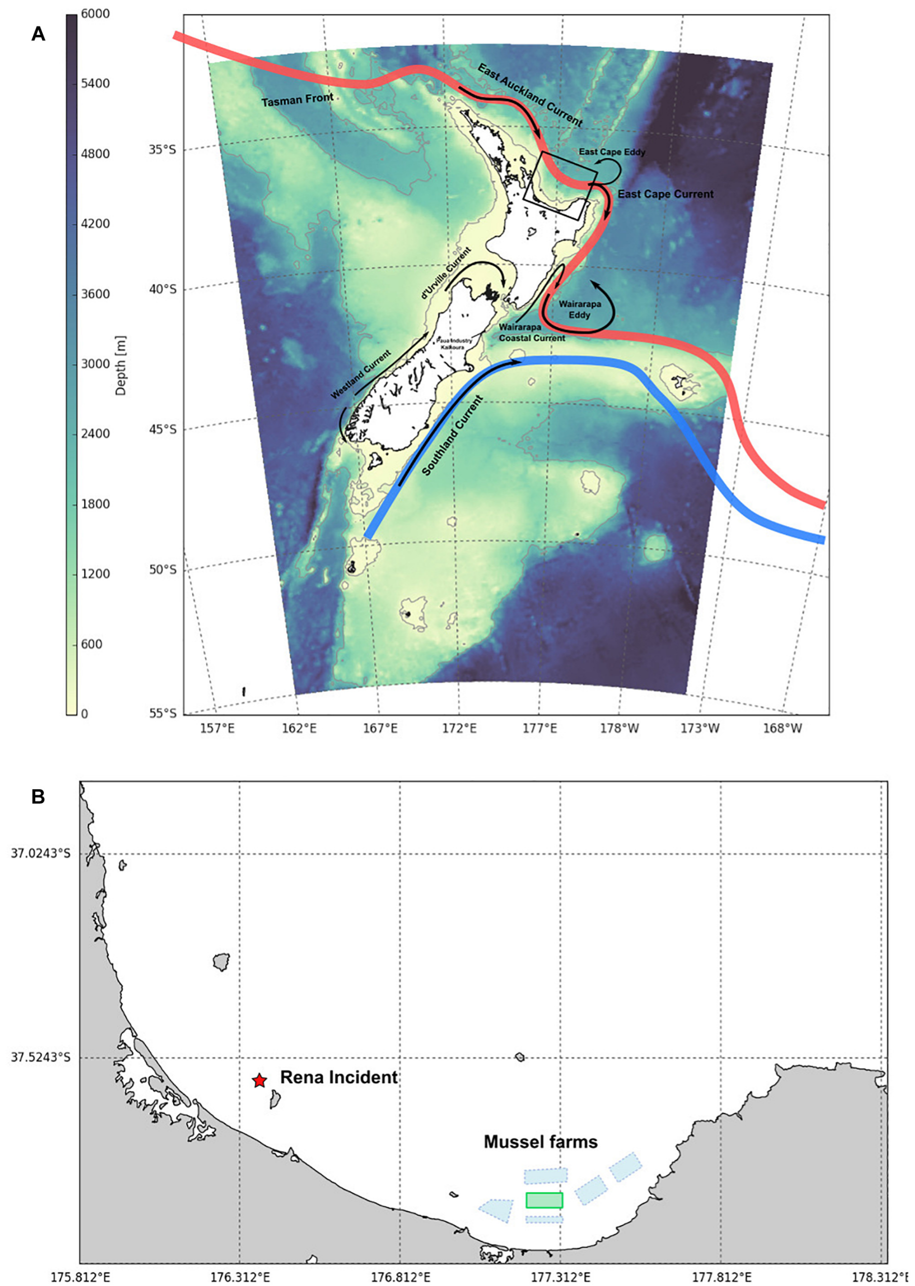

FIGURE 2 | Diagram showing the **(A)** NZ maritime region and the dominant circulation and **(B)** regional zoom in of the Bay of Plenty region showing WMTB existing and proposed mussel farms. Adapted from https://www.moanaproject.org/nz-seafood under a Creative Commons public license Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0).

- Determine how data and information about people, wildlife, and environment are collected, stored, used, and shared.

Case Study Overview

The subject of this case study is the project "Connecting Inuit Knowledge with sea-ice research to better understand changing conditions for sea-ice freeze-up and break-up." This joint initiative includes the communities of Kugluktuk, Cambridge Bay, Gjoa Haven, and Iqaluit, in the territory of Nunavut in Inuit Nunangat, together with ONC, the University of Victoria, Nunavut Arctic College, and groups within two federal government departments: Environment and Climate Change Canada [ECCC (CIS)], and Fisheries and Oceans Canada. Formally, the project has five objectives:

1. Work with knowledgeable hunters, Elders, youth, and other community members to identify changes in sea-ice

FIGURE 3 | A map of Ocean Networks Canada's community observatory and community engagement locations.

and the impact on community activities such as hunting, fishing, transportation, recreation, and other activities.
2. Provide opportunities for youth to engage in science in all communities.
3. Implement a community-based water and ice monitoring program with Canadian Rangers and Fisheries and Oceans Canada.
4. Develop sea-ice products for community use with the Canadian Ice Service (CIS).
5. Launch a new Instrument Technology course with Nunavut Arctic College.

The science goals of the project, centered on sea-ice, include an analysis of variables such as sea-ice thickness, growth, and decay as well as changes in dates of freeze-up and break-up in different regions. ECCC, a Canadian government department, is a partner in this initiative through the CIS and expects to gather local input that will allow them to tailor information, such as sea-ice charts and other sea-ice data products, to address community needs with support from Ocean Networks Canada in delivering those products. The project also aims to identify next steps for ocean and sea-ice monitoring programs, data needs, education, and training programs according to community priorities. The project is funded through a Canadian government granting program from Polar Knowledge Canada (POLAR) with support from ONC.

One of the main project elements is to have knowledgeable hunters and Elders identify specific changes in sea-ice formation and decay, and thickness and stability, that have an impact on residents or their activities. The information provided by these community members, along with data collected by the ONC community observatory in Cambridge Bay and remote sensing (satellite) of ice cover and concentration, will co-contribute to knowledge on local ice conditions.

Methodological Background

The formal integration of TK in ecological research dates back to the 1980s (e.g., Johannes, 1981; Berkes, 1999; Ford and Martinez, 2000), but few studies have discussed the key elements and techniques that use different knowledge systems (e.g., Huntington et al., 2002; Parrado-Rosselli, 2007; Brook et al., 2009). This project draws from methods in the social sciences such as interviews, workshops, local observations, and mapping exercises during the workshops and interviews. Briggs (1986) and Huntington (1998) have documented the use of interviews on ecological research. Huntington et al. (2002) also used workshops while mapping exercises have been documented in Naidoo and Hill (2006) and Murray et al. (2008).

Methods

Collaborative project planning, execution, and reporting

Collaboration between local residents, academic researchers, and government staff via regular conference calls, joint preparation, planning and project execution has been key to the success of this effort from the beginning of the project.

Establishing an oversight committee

Collaborative research is achieved through a project Oversight Committee (OC), established in each community. These committees have representatives from each main community organization: the Hunters and Trappers Organization, Hamlet, and the Kitikmeot Inuit Associations in Cambridge Bay, Kugluktuk, and Gjoa Haven. The OC guides research priorities and identifies community participants for workshops and interviews. The OC also keep their respective organizations informed on project activities. The OC ensures that TK is shared in the project by identifying Elders and knowledgeable hunters to participate in interviews, workshops, and field trip activities.

Workshops

Elders and local experts participated in workshops in November 2017, July 2018, and November 2018, to identify representative community sites to be monitored, and information to be collected. For example, in Kugluktuk, workshop participants identified two areas of interest for monitoring sea-ice conditions along the channel/bay: (i) Marker Island or Seven Mile Island, where ship traffic and sound could be monitored alongside water properties and ice thickness, and (ii) the mouth of the Coppermine River where they conduct their fishing activities, and fresh water mixes with saltwater. Sea-ice safety has been a common concern in all of these communities. During interviews in Cambridge Bay in November 2017, and in Kugluktuk, in November 2018, Elders identified an interest in measuring snow and ice thickness and growth along common travel routes and identified areas of concern where ice thickness can be unsafe for travel due to ocean currents and wind conditions.

Interviews

Face-to-face semi-directed interviews are being conducted with key community knowledge holders. The interviews are audio recorded and transcribed for analysis, and also allow the science team to build relationships in the community to understand the broader social and cultural context of the project. The interview questions have focused on the topics of snow and ice conditions, freeze-up and break-up dates, impacts of changes, information needs, and weather observations, among others.

Site visits

Multiple field trips were made from each community. TK was used to select the field sites to ensure that they represented local environmental variability in places relevant to the communities' subsistence activities and travel routes. Elder hunters, academic researchers and government staff traveled by snowmobile to these sites in order to document typical conditions and locations where significant changes in sea-ice conditions had been observed. The field teams took measurements and made observations using traditional methods and instrument technology on the travel routes. In other words, participants collaborated by doing, not only talking, to learn from each other in the practice of documenting sea-ice conditions. This information was then discussed with the Elders and workshop participants in Cambridge Bay and Kugluktuk after the trips and during a workshop in Gjoa Haven. It is also expected that this type of information will serve as a basis for funding applications for equipment purchases and deployment at monitoring stations.

The field trips also enabled the ONC team, government staff and community residents to share a common experience that set the stage for developing stronger relationships in subsequent site visits. Even simple pieces of information are critical to developing a common language and understanding; for example, it was learned that community members better understood ice thickness measurements in inches rather than metric units. The site visits were particularly relevant for scientists and government staff in terms of understanding the use of sea-ice for different activities and learning about the ice types that are considered safe. For example, residents feel that at three inches (7.5 cm), the ice is strong enough for a person to walk on and at five to six inches (12–15 cm), it is safe for travel by snowmobile. Elders consider the ice to be completely safe for any activity when it is one to one-and-a-half feet (30–45 cm) thick.

Co-development of education and training programs

The communities involved in this project, and many of the other communities with which ONC collaborates, are rich in TEK, LEK, and IK, and yet do not typically have a depth of resident scientific expertise. While the science and government teams have funding to visit communities and learn from Elders and knowledge holders in the community, youth and adults in the community who wish to further engage in science have limited opportunities to pursue training in their communities. In order to have true two-way partnerships, it is necessary to create local training opportunities. In this project, a full college-level course in Instrument Technology has been developed and integrated into the curriculum of the Environmental Technology Program at Nunavut Arctic College.

Furthermore, part-time Youth Science Ambassadors have been hired in each community to act as mentors for other youth with an interest in science. ONC's Ocean Sense program, facilitated by the Youth Science Ambassadors, enables students to gain a cross-cultural understanding of the ocean by incorporating ocean science and Inuit knowledge of the ocean into education resources and activities which are co-developed with community educators. The goal of these programs is to increase interest and create opportunities for Inuit and northern students, who are underrepresented in science, to be directly engaged in local research and the transfer of Inuit knowledge.

Data and information sharing

Conference calls with the Oversight Committee and annual (or more frequently as travel permits) public meetings are held in each community to update community members on the project progress and to seek broad input on project activities. All results from the project will be translated into local language and communicated in oral and written form to the communities. A key outcome will also be the joint development of data products specifically designed to meet community needs as determined from community feedback collected through the means described above.

Summary

Potential outcomes from this project for the communities include: enhanced community and personal safety, community resiliency, and the potential for economic opportunity, employment and training; a strengthened network for community monitoring; and data products which combine local information with scientific data. Conducting the project in true partnership has been enriching for all participants and is also essential to the scientific success and community relevance of the outcomes.

The original project timeline was from April 2017 to March 2019, although the project builds on engagement in one community, Cambridge Bay, ongoing since 2012. In response to high community interest, additional funding has been secured with support from ECCC to continue examining the need for community-oriented ice data products through to March 2021. Additional funding proposals for monitoring programs, training, and youth engagements are currently in progress.

FURTHER EXAMPLES

Theory and Practice of Resource Use and Governance Systems in Context

In addition to monitoring the physical and bio-geochemical properties of ocean change, monitoring human behavior is a common need. For example, fishing areas under strict regulations but with no property rights in open access zones are often overexploited. This occurs when short run incentives motivate fishers to intensively harvest the resource before any other fisher is able to do so (Gordon, 1954; Hardin, 1968). Similarly, unenforced property rights due to, e.g., lacking monitoring and enforcement resources, have resulted in overharvesting by third parties not entitled to the resources under international law; examples throughout Pacific Islands, particularly for tuna species, abound (Hanich et al., 2010; Rohe et al., 2017).

Significant progress has been made in cooperative monitoring and technology transfer between major fishing nations and local communities (Dunn et al., 2018). Satellite-based monitoring capabilities are rapidly evolving through AIS, and significant gains are being achieved through monitoring mechanisms such as Global Fishing Watch. This is part of a global effort to combat illegal, unreported and unregulated (IUU) fishing, which can impact all types of fisheries and can impose costly damages to marine ecosystems, global food security and local economies (FAO, 2010; Schatz, 2016). In curbing IUU, monitoring and enforcement simultaneously protect a broad range of socio-ecological conditions and provide a platform for further environmental condition monitoring instrumentation.

Ecosystem-based management approaches can mitigate overexploitation of natural resources in communities with few monitoring and enforcement resources. These include the establishment of various forms of marine protection, e.g., no-take zones, marine spatial planning, and Rights-Based Fisheries Management (RBFM). All share a goal of increasing ecosystem health and resilience (Hilborn et al., 2006) by using management techniques that promote sustainable resource use (Gelcich et al., 2006; Cancino et al., 2007; Uchida et al., 2012).

RBFM offers authorized fishers' exclusive access to harvesting marine resources while strictly excluding unauthorized fishers (Wilen et al., 2012). Individual Transferable Quotas (ITQs), fishing cooperatives, and Territorial Use Rights in Fisheries (TURFs) are the three different forms under which RBFM operates. ITQs and fishing cooperatives are both efficient management techniques, albeit with differing emphasis on decision-making and the role of the commercial fisheries within the greater ecosystem (Arnason, 2012; Deacon, 2012; Yagi et al., 2012). Implementing ITQs can have negative distributional impacts for communities that cooperative agreements may more easily resolve. As NZ's perpetual ITQs have shown, ITQs can create and exacerbate imbalances in terms of who stands to benefit from both ecosystem use and its long run conservation, by assigning strong but incomplete rights to only a subset of interest groups (Hersoug, 2018). Furthermore, ITQ systems cannot easily incorporate multiple species, even when the commercial fisheries dynamics are well understood (Cancino et al., 2007; Wilen et al., 2012).

Ecosystems that have multiple users, including Indigenous communities, who rely on overlapping components of a shifting and uncertain ecosystem, require system monitoring and regulation that acknowledges and acts to sustain a set of marine system productivities that extends beyond an individual species. At the same time it must be more cognizant of the socio-ecological conditions relying on those productivities. One option for this broader consideration is the use of TURFs (Auriemma et al., 2014), particularly community-managed ones. These offer greater flexibility on harvest and rights and may cover a wide variety of community and ecosystem issues. Defined boundaries and rights are given to specific community-sanctioned fishers as a function of their geographic location (Cancino et al., 2007; Wilen et al., 2012).

TURFs help overfished fisheries recover and steer the environment toward long-term sustainability. Inshore Japanese fisheries, for example, have operated under a wide range of TURF arrangements for centuries. The main drawback of TURFs occurs when there is considerable exchange in and out of the TURFs without accompanying negotiation mechanisms between governance regimes. This is in many ways analogous to challenges faced by local and Indigenous communities whose ecosystems are put at risk by activities from outside the system.

Large-Scale Data Collection, Integration, and Dissemination

Marine ecosystems are put under constant pressure due to global-scale anthropogenic activities such as high seas overexploitation, pollution, eutrophication, and introduced species (Halpern et al., 2008; Hoegh-Guldberg and Bruno, 2010; Burrows et al., 2011), and global effects, such as ocean acidification and climate change (Doney et al., 2012; AMAP, 2018). These stressors have a great altering effect on marine ecosystems functioning, decreasing the amount of goods and services that they can provide (Worm et al., 2006; Crain et al., 2008). Hence, monitoring marine ecosystems to understand these stressors' consequences on the marine ecosystem functioning is critically needed (Danovaro et al., 2008; Nõges et al., 2016; Zeppilli et al., 2016) to help identify sustainable and cost-effective solutions that governments and communities will be able to apply.

Examples of large-scale, integrated portals that have emerged in recent years include the Integrated Ocean Observing System, and the Marine Biodiversity Observation Network (MBON), a thematic network within the Group on Earth Observations Biodiversity Observation Network (GEO BON). These global organizations assemble disparate scientific observations so researchers and decision-makers better understand local and regional impacts, ecosystem feedback mechanisms, teleconnections, and ocean change.

GEO BON is a multinational and multi-organizational partnership initiated in 2008. Its activities operate through scientific working groups in conjunction with Biodiversity Observation Networks arranged by geography or theme, including MBON[8]. GEO BON's structure is continually evolving to facilitate and help inform assessment and decision making by various levels, from governments to individuals, by providing state of the global environment information (Tallis et al., 2012). The partnership cooperates with the UN Convention on Biological Diversity and the International Protocol on Biodiversity and Ecosystem Services, further integrating monitoring and governance efforts.

GEO BON is incorporating information on biophysical and social tendencies, on existing databases, resources and ecosystem services in governance and decision-making, to fill gaps in observation systems, and to create protocols for new ecosystem services or observations that are currently without guidelines. Its main focus remains, however, on the national scale. A tradeoff continues between access to more conventional, consistent and replicable data and information and more community-integrated data and information whose origins, needs and uses may be more specific and less transferable to other communities and scenarios.

In general, the globally scaled observation systems are not well-integrated into socio-ecological systems or local and Indigenous communities, particularly where poor connectivity hinders information transfer and/or systems are isolated from substantial trade. Feedback effects and the consequences of ecosystem degradation and biodiversity loss for human well-being at the appropriate scale are missed. To better understand monitoring needs, an ecosystem supply chain can be imagined. Any socio-ecological system depends on (1) supply as a function of the biophysical potential, (2) services that indicate the location and activities of the beneficiaries, and (3) benefits that locate societal preferences and human well-being. Trade-offs result from the biophysical and cultural limits of this socio-ecological system (Nelson et al., 2009). When the biophysical limits and feedbacks are understood and monitored clearly in the context of cultural limits and changing conditions requiring human responses, the systems become more adaptable and resilient.

Alternatives to national statistics can supplement these accounts. For example, field-based observations, including those from local and Indigenous communities, may offer a more differentiated spatial analysis of supply chains with wider services (Nelson et al., 2009). Remote sensing can inform assessment of ecosystem service changes and biodiversity conditions, from a local to global scale, over time (Hibbard et al., 2010). Remote sensing is too infrequently employed at a global scale to create a reliable and usable monitoring platform system, however, it remains a promising technique for monitoring water quality (Matthews et al., 2010). Furthermore, progress through new technologies, e.g., the Nested Environmental status Assessment Tool, is improving the ability to aggregate and disaggregate existing data at scales that bridge gaps between marine systems and the people who depend upon them (Borja et al., 2019).

Numerical simulations (models) can fill the gaps left by field-based observations. Models provide quantitative outputs regarding ecosystem services' conditions, changes, and distribution based on ecosystem understanding and dynamics (Tallis et al., 2012; Piroddi et al., 2015; Lynam et al., 2016). Models can also directly incorporate socio-ecological system decision-making and human feedback loops into information systems (Kaiser and Roumasset, 2014). This moves monitoring from an accounting process toward becoming a management tool. As monitoring efforts progress, models must not oversimplify the connections of local and Indigenous communities to resource stewardship.

Community-Focused Data Sharing Creates Actionable Information

Large, international data repositories as information-sharing tools can present challenges for communities. Here are some of the major challenges, and ideas and recommendations for alternatives. The challenges include: (1) internet connectivity in remote communities; (2) training and capacity building needs for data interpretation; (3) integrating scientific data and IK, and (4) multi-modal data-sharing.

Many coastal communities distant from main population centers or transportation routes do not have access to reliable, high-speed internet. For example, the Arctic communities of Kugluktuk, Cambridge Bay, and Gjoa Haven, featured in the Canadian case study, rely on satellite internet connectivity with limited bandwidth shared by the entire community. Although telephone/internet connectivity is rapidly changing (e.g., Kugluktuk and Cambridge Bay recent upgraded to 4G cellular networks, but Gjoa Haven does not yet have cellular service), it will be decades before all remote community members have high-speed internet.

Low-bandwidth versions of websites or locally hosted data repositories can enable community access. In addition, data formatting and content should match end-user needs, which may include mobile access and varying time scales, including the present and future. When data portals are accessible in communities, there is a further challenge in that the community members and decision-makers may not be familiar with the data presentation, units of measurement, instrumentation, and applications of the data.

Data availability is a start but providing support and training to the community to use the data is equally important. Data products must be designed with community members in mind, for example, by incorporating local place names and language alongside scientific units and interpreting data online in publicly accessible language and in public venues, e.g., at the local store or hunter's office.

Data products must further acknowledge that the information stream is multi-directional. As a goal of this paper is to inform co-management and policy through data from both scientific and IK-based research methods (including TEK and LEK), it is necessary to collect and present the data in a way that recognizes the contribution of these data sources. This poses a data compatibility challenge as data are of different types and formats. Effective study designs will plan to include both scientific and IK data from the outset. Northern Norway's BarentsWatch[9]

[8]https://geobon.org/bons/thematic-bon/mbon (accessed May 29, 2019).

[9]https://www.barentswatch.no/en (accessed May 29, 2019).

is one such technology-driven community-based monitoring and data collection for marine conditions, fisheries governance, and other vital coastal information. More research is needed, however, on methods and practices for making effective use of scientific and IK for ecological monitoring and decision-making, particularly where communities are not as digitally connected as the northern Norwegian coast.

In Indigenous communities, information is often shared informally through phone calls, face-to-face conversations, and social media (Facebook). Community members and guests also use printed maps and observations in central locations in the community, i.e., a shop or community center. For scientists involved in community-engaged research, knowledge mobilization cannot rely solely on scientific publications or white papers. Communities must be involved in deciding how research and monitoring results are shared. Public meetings, local project contacts, and spokespeople are key components to understanding the formats and means that are familiar and meaningful to the community.

Monitoring Tools That Bridge Scales

The Salienseas project[10] aims at "co-production of marine climate services," in response to the above challenges, and those of transport between isolated coastal Arctic communities. The project is bringing together end-users of Arctic climate information, including TEK and IK holders and users in Greenland, with large private and public sector providers of climate monitoring services, to provide monitoring tools that bridge local, regional, and global scales.

Recent ocean acidification monitoring and assessment efforts by the Arctic Monitoring and Assessment Program (AMAP) aim to link monitoring and assessment with end-users. The 2018 Arctic Ocean Acidification AMAP Assessment started with the goal of establishing end-to-end modeling of the bio-geological processes, ecological and socio-economic risks, and threats from changing ocean pH levels in the circumpolar Arctic. The assessment's goals evolved over the years as the realities of truly integrated interdisciplinary research with cross-cultural interest groups became clear. Groups emphasized that context always matters and there is rarely, if ever, a simple formula for benefits transfer (Newbold et al., 2018) from one ecosystem, community, geo-physical system, or socio-ecological system, to another. Furthermore, knowledge production is non-linear, and should not be "top-down." The end result is six case studies on individual Arctic socio-ecological systems potentially at risk for ocean acidification impacts (AMAP, 2018). Taken together, the studies highlight how communities need to act even when the science is imperfect and incomplete, and therefore require multidimensional and inclusive processes to scientific investigation, IK, and how accumulated knowledge is used, distributed, and built into future decisions.

This means that large scale monitoring, using new *in situ* technologies and remote sensing (Turner et al., 2003; Blondeau-Patissier et al., 2004; Pettorelli et al., 2014), must be connected to community well-being to be meaningful community investments. Five *in situ* instruments used to monitor marine abiotic and biotic changes are discussed in this context: chemical sensors, seabed observatories, underwater autonomous and integrated monitoring, biosensors, and acoustic monitoring.

Chemical sensors monitor concentrations of heavy metals, organic pollutants and algal toxins (Danovaro et al., 2016). In many cases, pollutant sources and the communities affected by the pollution are separated by wide distances. How sensors directly identify health threats and indirectly identify pollution sources and assess mechanisms for stemming pollution streams should be considered.

Seabed observatories (video cameras on Remotely Operated Vehicles and autonomous underwater vehicles) represent powerful, non-destructive tools for studying benthic organisms' dynamics. Seabed research has historically focused on mineral resources rather than communities' ecosystem foundations. However, seabed observatories are increasing understanding of continental margin and deep-sea ecosystems' biodiversity and functioning and shifting the focus back to communities, especially if locals are directly involved in the deployment and monitoring (Solan et al., 2003; Stoner et al., 2008; Danovaro et al., 2016). One promising new underwater autonomous and integrated monitoring technology to follow is CLEAN SEA (Continuous Long-term Environmental and Asset iNtegrity monitoring at SEA) (Danovaro et al., 2016).

Nature, too, provides *in situ* monitoring tools. Bivalves are filter feeders that serve as good biosensors to evaluate localized water quality. Bivalves are high frequency non-invasive (HFNI) "valvometers" that can provide conventional monitoring in human-impacted areas, e.g., harbors, oil platforms and aquaculture (Andrade et al., 2016). LEK, TEK and community use of bivalves provide a good pivot point for aligning interests across science and IK.

Finally, monitoring the undersea acoustics and the impacts of noise pollution on marine organisms is increasing as the ocean soundscape becomes more crowded with, for example, vessel noise, air gun arrays from seismic exploration, and long range sonar for military uses. Understanding how marine organisms that produce sounds (mammals and invertebrates) for communication, reproduction, predation, etc., is needed to make decisions over local and distant sound emissions to balance local communities' needs with global, commercial drivers of sound emissions (Danovaro et al., 2016).

DISCUSSION

New technologies and capabilities for ocean monitoring will be useful and successful if there is uptake by interest groups. The challenges of large-scale monitoring, information collection and transfer outside the main pathways include: appropriate physical and human scales for monitoring; sharing information in timely and meaningful ways; combing science with TEK, LEK, and IK in beneficial ways; and how results are used.

As technology and information sharing rapidly transform, the access gap between communities may widen, and those

[10]http://www.salienseas.com/ (accessed March 10, 2019).

distant from an increasingly globalized stream of data may be passive receptors of ocean monitoring decisions and ocean change itself, rather than co-creators of knowledge and regulation, governing, monitoring, and their outcomes.

Monitoring human behavior is as important as monitoring bio-geochemical changes. Improving livelihoods will be more effective if misaligned incentives are targeted directly rather than targeting ecosystem functions in uncertain, complex, socio-ecological systems. Local and Indigenous communities that depend on ocean resources and hold knowledge systems that differ from conventional science provide excellent understanding of this.

Two case studies in NZ and Canada provide an overview of how connections between communities and monitoring can evolve. The in-depth case studies highlight real-world examples of connecting Indigenous and wider community information with scientific data from monitoring programs. Recommendations for successful collaboration to improve societal outcomes are also given. The areas of collaboration include:

- Identifying scientific and community stakeholders and interested parties.
- Co-developing funding proposals and project plans.
- Sharing community and scientific information on local environmental concerns, important/sensitive locations, other related research projects, instrument deployments, educational needs and opportunities, and additional partners.
- Regular interactions through face-to-face meetings, workshops and personal communications.
- Jointly installing monitoring equipment: site surveys, permits, permissions, shore infrastructure development, above-water and underwater sensor deployment.
- Co-developing educational resources: collaborating with educators to create suitable materials for local needs appropriately including TEK, LEK, and IK.
- Jointly developing data products and services according to community needs.
- Ongoing engagement through sharing data and results, connecting to broader Indigenous and scientific environmental monitoring communities.
- Connecting environmental and bio-geochemical process monitoring with human behavior monitoring in the community context.

The authors' experiences in these projects have been rewarding. We hope these studies provide inspiration to others involved in ocean monitoring to embrace the benefits of connecting scientists, local communities and IK holders and their respective knowledge systems for improved marine ecosystem management.

Global change is undeniably occurring and we cannot manage this change without monitoring it. The scale of this monitoring continues to expand, and new technologies and information systems are driving pushes for standardization, global systems, user-friendly interfaces and international networks. The global scale presents challenges in transmitting the information between community use and governance scales that can and should be addressed with feedback mechanisms and communication with local communities.

AUTHOR CONTRIBUTIONS

BK, NH, KM, MR, KS, and DP scoped and structured the manuscript. BK, NH, AS, MH, and NTL contributed to the introduction, theory, literature review, and discussion. KM, MR, KS, and DP contributed to writing and reviewing the NZ case study. MH and LE-M contributed to writing the Canadian case study. MR contributed to **Figures 1**, **2**. SJ and CH provided the editorial support and preparatory discussions. BK, KM, NH, MH, and SJ reviewed the manuscript.

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REFERENCES

Addison, P. F. E., Collins, D. J., Trebilco, R., Howe, S., Bax, N., Hedge, P., et al. (2018). A new wave of marine evidence-based management: emerging challenges and solutions to transform monitoring, evaluating, and reporting. *ICES J. Mar. Sci.* 75, 941–952. doi: 10.1093/icesjms/fsx216

Alaska Native Tribal Health Consortium [ANTHC] (2018). *The LEO Network*. Available at: https://www.leonetwork.org/ (accessed May 19, 2019).

AMAP (2018). *AMAP Assessment 2018: Arctic Ocean Acidification*. Tromsø: Arctic Monitoring and Assessment Programme (AMAP).

Andrade, H., Massabuau, J. C., Cochrane, S., Ciret, P., Tran, D., Sow, M., et al. (2016). High frequency non-invasive (HFNI) bio-sensors as a potential tool for marine monitoring and assessments. *Front. Mar. Sci.* 3:187. doi: 10.3389/fmars.2016.00187

Arnason, R. (2012). Property rights in fisheries: how much can individual transferable quotas accomplish? *Rev. Environ. Econ. Policy* 6, 217–236. doi: 10.1093/reep/res011

Auriemma, G., Byler, K., Peterson, K., Yurkanin, A., and Costello, C. (2014). *A Global Assessment of Territorial Use Rights in Fisheries to Determine Variability in Success and Design*. Santa Barbara, CA: Bren School of Environmental Science and Management.

Bax, N. J., Appeltans, W., Brainard, R., Duffy, J. E., Dunstan, P., Hanich, Q., et al. (2018). Linking capacity development to GOOS monitoring networks to achieve sustained ocean observation. *Front. Mar. Sci.* 5:346. doi: 10.3389/fmars.2018.00346

Berkes, F. (1999). *Sacred Ecology: Traditional Ecological Knowledge and Resource Management*. Philadelphia, PA: Taylor & Francis.

Berkes, F. (2009). Indigenous ways of knowing and the study of environmental change. *J. R. Soc. N. Z.* 39, 151–156. doi: 10.1080/03014220909510568

Berkes, F., Colding, J., and Folke, C. (2000). Rediscovery of traditional ecological knowledge as adaptive management. *Ecol. Appl.* 10, 1251–1262. doi: 10.1890/1051-0761(2000)010%5B1251:roteka%5D2.0.co;2

Blondeau-Patissier, D., Tilstone, G. H., Martinez-Vicente, V., and Moore, G. F. (2004). Comparison of bio-physical marine products from SeaWiFS, MODIS and a bio-optical model with in situ measurements from Northern European waters. *J. Opt. A* 6, 875–889. doi: 10.1088/1464-4258/6/9/010

Borja, A., Garmendia, J. M., Menchaca, I., Uriarte, A., and Sagarmínaga, Y. (2019). Yes, we can! large-scale integrative assessment of european regional seas, using open access databases. *Front. Mar. Sci.* 6:19. doi: 10.3389/fmars.2019.00019

Briggs, C. L. (1986). *Learning How to Ask: A Sociolinguistic Appraisal of the Role of the Interview in Social Science Research*. Cambridge: Cambridge University Press.

Brook, R. K., Kutz, S. J., Veitch, A. M., Popko, R. A., Elkin, B. T., and Guthrie, G. (2009). Fostering community-based wildlife health monitoring and research in the Canadian North. *EcoHealth* 6, 266–278. doi: 10.1007/s10393-009-0256-7

Burrows, M. T., Schoeman, D. S., Buckley, L. B., Moore, P., Poloczanska, E. S., Brander, K. M., et al. (2011). The pace of shifting climate in marine and terrestrial ecosystems. *Science* 334, 652–655. doi: 10.1126/science.1210288

Busch, J., Bardaji, R., Ceccaroni, L., Friedrichs, A., Piera, J., Simon, C., et al. (2016). Citizen bio-optical observations from coast- and ocean and their compatibility with ocean colour satellite measurements. *Remote Sens.* 8:879. doi: 10.3390/rs8110879

Cancino, J. P., Uchida, H., and Wilen, J. E. (2007). TURFs and ITQs: collective vs. individual decision making. *Mar. Resour. Econ.* 22, 391–406. doi: 10.1086/mre.22.4.42629569

Chaturvedi, S. (2016). The circumpolar "Socal Natural Sciences" laboratories: knowledges, values and practices. *Polar J.* 6, 201–208. doi: 10.1080/2154896x.2016.1262232

Chiba, S., Sonia, B., Corinne, S. M., Sarah, I., Patricia, M., and Lauren, V. W. (2018). Zooplankton monitoring to contribute towards addressing global biodiversity conservation challenges. *J. Plankton Res.* 40, 509–518. doi: 10.1093/plankt/fby030

Clark, M. J. R., MacDonald, D. D., Whitfield, P. H., and Wong, M. P. (2010). Designing monitoring programs for water quality based on experience in Canada II. Characterization of problems and data-quality objectives. *TrAC Trends Analyt. Chem.* 29, 385–398. doi: 10.1016/j.trac.2010.02.005

Costello, C., Ovando, D., Hilborn, R., Gaines, S. D., Deschenes, O., and Lester, S. E. (2012). Status and solutions for the world's unassessed fisheries. *Science* 338, 517–520. doi: 10.1126/science.1223389

Crain, C. M., Kroeker, K., and Halpern, B. S. (2008). Interactive and cumulative effects of multiple human stressors in marine systems. *Ecol. Lett.* 11, 1304–1315. doi: 10.1111/j.1461-0248.2008.01253.x

Crise, A. M., Ribera, D., Alcala, M., Patrizio, M., George, P., Julie, R., et al. (2018). A conceptual framework for developing the next generation of Marine OBservatories (MOBs) for science and society. *Front. Mar. Sci.* 5:318. doi: 10.3389/fmars.2018.00318

Danovaro, R., Carugati, L., Berzano, M., Cahill, A. E., Carvalho, S., Chenuil, A., et al. (2016). Implementing and innovating marine monitoring approaches for assessing marine environmental status. *Front. Mar. Sci.* 3:213. doi: 10.3389/fmars.2016.00213

Danovaro, R., Gambi, C., Dell'Anno, A., Corinaldesi, C., Fraschetti, S., Vanreusel, A., et al. (2008). Exponential decline of deep-sea ecosystem functioning linked to benthic biodiversity loss. *Curr. Biol.* 18, 1–8. doi: 10.1016/j.cub.2007.11.056

Deacon, R. T. (2012). Fishery management by harvester cooperatives. *Rev. Environ. Econ. Policy* 6, 258–277. doi: 10.1093/reep/res008

DeFries, R., Pagiola, S., Adamowicz, W. L., Akcakaya, H. R., Arcenas, A., Babu, S., et al. (2005). Analytical approaches for assessing ecosystem condition and human well- being. *Ecosyst. Hum Well Being Curr. State Trends* 1, 37–71.

Dickinson, J. L., Shirk, J., Bonter, D., Bonney, R., Crain, R. L., Martin, J., et al. (2012). The current state of citizen science as a tool for ecological research and public engagement. *Front. Ecol. Environ.* 10, 291–297. doi: 10.1890/110236

Doney, S. C., Ruckelshaus, M., Duffy, J. E., Barry, J. P., Chan, F., English, C. A., et al. (2012). Climate change impacts on marine ecosystems. *Ann. Rev. Mar. Sci.* 4, 11–37.

Dunn, D. C., Caroline, J., Guillermo, O., Crespo, D. J., McCauley, D., Kroodsma, K. B., et al. (2018). Empowering high seas governance with satellite vessel tracking data. *Fish Fish.* 19, 729–739. doi: 10.1111/faf.12285

FAO, U. (2010). *The State of World Fisheries and Aquaculture*. Rome: Food and Agriculture Organization of the United Nations.

Ford, J., and Martinez, D. (2000). Traditional ecological knowledge, ecosystem science, and environmental management. *Ecol. Appl.* 10, 1249–1340.

Gelcich, S., Edwards-Jones, G., Kaiser, M. J., and Castilla, J. C. (2006). Co-management policy can reduce resilience in traditionally managed marine ecosystems. *Ecosystems* 9, 951–966. doi: 10.1007/s10021-005-0007-8

Gibbs, M. (2001). Toward a strategy for undertaking cross-cultural collaborative research. *Soc. Natl. Res.* 14, 673–687. doi: 10.1080/08941920120547

Glomsrød, S., Duhaime, G., and Aslaksen, I. (2017). "The economy of the north 2015," in *Statistical Analyses*, eds S. Glomsrød, G. Duhaime, and I. Aslaksen (Oslo: Statistisk sentralbyrå).

Gordon, H. S. (1954). *The Economic Theory of a Common-Property Resource: the Fishery. In Classic Papers in Natural Resource Economics*. London: Palgrave Macmillan, 178–203.

Gutiérrez, N. L., Hilborn, R., and Defeo, O. (2011). Leadership, social capital and incentives promote successful fisheries. *Nature* 470, 386–389. doi: 10.1038/nature09689

Halpern, B. S., Walbridge, S., Selkoe, K. A., Kappel, C. V., Micheli, F., D'agrosa, C., et al. (2008). A global map of human impact on marine ecosystems. *Science* 319, 948–952.

Hanich, Q., Teo, F., and Tsamenyi, M. (2010). A collective approach to Pacific islands fisheries management: moving beyond regional agreements. *Mar. Policy* 34, 85–91. doi: 10.1016/j.marpol.2009.04.018

Hardin, G. (1968). The tragedy of the commons. *Science* 162, 1243–1248.

Hardy, D., Patterson, M., Smith, H., Taiapa, C., and Matthias, R. (2015). "Cross-cultural environmental research processes, principles and methods - coastal examples from Aotearoa/New Zealand," in *The Handbook of Research Methods and Applications in Environmental Studies*, ed. R. Matthias (Northampton, MA: Edward Elgar Publishing).

Harmsworth, G., and Awatere, S. (2013). "Indigenous māori knowledge and perspectives of ecosystems. In Ecosystem services," in *New Zealand – Conditions and Trends*, ed. J. R. Dymond (Lincoln: Manaaki Whenua Press), 274–286.

Hepi, M., Foote, J., Makey, L., Badham, M., and Te Huna, A. (2018). Enabling mātauranga-informed management of the Kaipara Harbour, Aotearoa New Zealand. *N. Z. J. Mar. Freshwater Res.* 52, 1–14. doi: 10.1080/00288330.2018.1521845

Hersoug, B. (2018). "After all these years"–New Zealand's quota management system at the crossroads. *Mar. Policy* 92, 101–110. doi: 10.1016/j.marpol.2018.02.010

Hibbard, K., Janetos, A., van Vuuren, D. P., Pongratz, J., Rose, S. K., Betts, R., et al. (2010). Research priorities in land use and land-cover change for the Earth system and integrated assessment modelling. *Int. J. Climatol.* 30, 2118–2128. doi: 10.1002/joc.2150

Hikuroa, D. (2017). Mātauranga Māori—the ūkaipō of knowledge in New Zealand. *J. Roy. Soc. New Zeal.* 47, 5–10. doi: 10.1080/03036758.2016.1252407

Hilborn, R., Micheli, F., and De Leo, G. A. (2006). Integrating marine protected areas with catch regulation. *Can. J. Fish. Aquat. Sci.* 63, 642–649. doi: 10.1139/f05-243

Hoegh-Guldberg, O., and Bruno, J. F. (2010). The impact of climate change on the world's marine ecosystems. *Science* 328, 1523–1528. doi: 10.1126/science.1189930

Huntington, H. P. (1998). Observations on the utility of the semidirective interview for documenting traditional ecological knowledge. *Arctic* 51, 237–242.

Huntington, H. P., Brown-Schwalenberg, P. K., Frost, K. J., Fernandez-Gimenez, M. E., Norton, D. W., and Rosenberg, D. H. (2002). Observations on the workshop as a means of improving communication between holders of traditional and scientific knowledge. *Environ. Manag.* 30, 778–792. doi: 10.1007/s00267-002-2749-9

Inns, J. (2013). *Māori in the Seafood Sector (Fisheries and Aquaculture) – the Year in Review*. Available at: http://maorilawreview.co.nz/2013/06/maori-in-the-seafood-sector-fisheries-and-aquaculture-the-year-in-review/ (accessed August 28, 2018).

Inuit Tapiriit Kanatami [ITK] (2018). *National Inuit Strategy on Research*. Available at: https://www.itk.ca/national-strategy-on-research/ (accessed March 12, 20 and May 29, 2019).

Jackson, A.-M., Mita, N., and Hakopa, H. (2017). *Hui-te-ana-nui: Understanding Kaitiakitanga in our Marine Environment*. Report prepared for Ngā Moana Whakauka – Sustainable Seas National Science Challenge by Te koronga, School of Physical Education, Sport and Exercise Sciences (Dunedin: Otago University Press), 167.

James, P. A., Tidd, A., and Kaitu, L. P. (2018). The impact of industrial tuna fishing on small-scale fishers and economies in the Pacific. *Mar. Policy* 95, 189–198. doi: 10.1016/j.marpol.2018.03.021

Johannes, R. E. (1981). *Words of the Lagoon: Fishing and Marine Lore in the Palau District of Micronesia*. Berkeley, CA: University of California Press.

Joseph, R. (2017). Tūhonohono: tikanga māori me te ture; pākehā ki takutai moana. in *Proceedings of the Sustainable Seas Interface Conference* (New Zealand: University of Waikato)

Kaiser, B., and Roumasset, J. (2014). Transitional forces in a resource based economy: phases of economic and institutional development in hawaii. *Rev. Econ. Institut.* 5:44. doi: 10.5202/rei.v5i2.118

Kitson, J. C. (2004). Harvest rate of sooty shearwaters (Puffinus griseus) by Rakiura Māori: a potential tool to monitor population trends? *Wildlife Res.* 31, 319–325.

Kofinas, G., Lyver, P., Russell, D. E., White, R., Nelson, A., and Flanders, N. (2004). Towards a protocol for monitoring of caribou body condition. *Rangifer* 23, 43–52.

Krupnik, I., and Jolly, D. (2002). *The Earth is Faster Now: Indigenous Observations of Arctic Environmental Change*. Fairbanks, AK: Arctic Research Consortium of the United States.

Le Cornu, E., Angee, D. N., Elena, M. F., Gourlie, D., and Larry, C. B. (2018). Spatial management in small-scale fisheries: a potential approach for climate change adaptation in Pacific Islands. *Mar. Policy* 88, 350–358. doi: 10.1016/j.marpol.2017.09.030

Lessard, J., Osborne, J., Lauzier, R., Jamieson, G., and Harbo, R. (2002). *Applying Local and Scientific Knowledge to the Establishment of a Sustainable Fishery: the Zwest Coast Vancouver Island Goose Barnacle Fishery Experience. Fisheries Centre Research Reports*, Vol. 11. Vancouver, BC: University of British Columbia Press, 36–43.

Local Government New Zealand (2011). *Local Authorities and Māori: Case Studies of Local Arrangements*. Wellington: Local Government New Zealand.

Local Government New Zealand (2007). *Co-management: Case Studies Involving Local Authorities and Maori*. Wellington: Local Government New Zealand.

Lynam, C., Uusitalo, L., Patrício, J., Piroddi, C., Queiros, A., Teixeira, H., et al. (2016). Uses of innovative modelling tools within the implementation of the marine strategy framework directive. *Front. Mar. Sci.* 3:182. doi: 10.3389/fmars.2016.00182

Lyver, P. O. (2002). The use of traditional environmental knowledge to guide sooty shearwater (Puffinus griseus) harvests by Rakiura Māori. *Wildlife Soc. Bull.* 30, 29–40.

Lyver, P. O. B., Moller, H., and Thompson, C. (1999). Changes in sooty shearwater Puffinus griseuschick production and harvest precede ENSO events. *Mar. Ecol. Prog. Ser.* 188, 237–248. doi: 10.3354/meps188237

Māori Policy Unit. (2011). *Engaging with Maori A guide for staff of the Bay of Plenty Regional Council Te Tuhonotanga ki te Hunga Maori He Rauemi Hei Hapai Nga Kaimahi o Te Taiao a Toi*. Whakatane: Bay of Plenty Regional Council.

Matthews, M. W., Bernard, S., and Winter, K. (2010). Remote sensing of cyanobacteria-dominant algal blooms and water quality parameters in Zeekoevlei, a small hypertrophic lake, using MERIS. *Remote Sens. Environ.* 114, 2070–2087. doi: 10.1016/j.rse.2010.04.013

Miloslavich, P., Bax, N., Simmons, S. E., Klein, E., Appeltans, W., Aburto-Oropeza, O., et al. (2018a). Essential ocean variables for global sustained observations of biodiversity, and ecosystem changes. *Glob. Change Biol.* 24, 2416–2433. doi: 10.1111/gcb.14108

Miloslavich, P., Seeyave, S., Muller-Karger, F., Bax, N., Ali, E., Delgado, C., et al. (2018b). Challenges for global ocean observation: the need for increased human capacity. *J. Operat. Oceanog.* 1–20. doi: 10.1080/1755876X.2018.1526463

Ministry of Science Research and Technology (2005). *Vision Mātauranga: Unlocking the Innovation Potential of Māori Knowledge, Resources and People*. Tehran: Ministry of Science, Research and Technology.

Moller, H., Berkes, F., Lyver, P. O. B., and Kislalioglu, M. (2004). Combining science and traditional ecological knowledge: monitoring populations for co-management. *Ecol. Soc.* 9:2.

Moller, H., Charleton, K., Knight, B., and Lyver, P. (2009). Traditional ecological knowledge and scientific inference of prey availability: harvests of sooty shearwater (Puffinus griseus) chicks by Rakiura Maori. *N. Z. J. Zoo.* 36, 259–274. doi: 10.1080/03014220909510154

Moore, S. E., and Reeves, R. R. (2018). Tracking arctic marine mammal resilience in an era of rapid ecosystem alteration. *PLoS Biol.* 16:e2006708. doi: 10.1371/journal.pbio.2006708

Moore, S. E., Stabeno, P. J., Grebmeier, J. M., and Okkonen, S. R. (2018). The Arctic Marine Pulses Model: linking annual oceanographic processes to contiguous ecological domains in the Pacific Arctic. *Deep Sea Res. Part 2 Top Stud. Oceanogr.* 152, 8–21. doi: 10.1016/j.dsr2.2016.10.011

Muller-Karger, F., Patricia, M., Nicholas, B. J., Samantha, E. S., Mark, J., Ward, B., et al. (2018). Advancing marine biological observations and data requirements of the complementary essential ocean variables (EOVs) and essential biodiversity variables (EBVs) frameworks. *Front. Mar. Sci.* 5:211.

Murray, G., Neis, B., Palmer, C. T., and Schneider, D. C. (2008). Mapping cod: fisheries science, fish harvesters' ecological knowledge and cod migrations in the northern Gulf of St. Lawrence. *Hum. Ecol.* 36, 581–598. doi: 10.1007/s10745-008-9178-1

Naidoo, R., and Hill, K. (2006). Emergence of indigenous vegetation classifications through integration of traditional ecological knowledge and remote sensing analyses. *Environ. Manag.* 38, 377–387. doi: 10.1007/s00267-004-0338-9

Nana, G., Stokes, F., Molano, W. (2011) *The Asset Base, Income, Expenditure, and GDP of the 2010 Maori Economy*. Available at: https://www.tpk.govt.nz/en/a-matou-mohiotanga/business-and-economics/the-asset-base-income-expenditure-and-gdp-of-the-2 (accessed August 28, 2018).

Nelson, E., Mendoza, G., Regetz, J., Polasky, S., Tallis, H., Cameron, D., et al. (2009). Modeling multiple ecosystem services, biodiversity conservation, commodity production, and tradeoffs at landscape scales. *Front. Ecol. Environ.* 7, 4–11. doi: 10.1890/080023

Newbold, S., Simpson, R. D., Massey, D. M., Heberling, M. T., Wheeler, W., Corona, J., et al. (2018). Benefit transfer challenges: perspectives from US practitioners. *Environ. Resour. Econ.* 69, 467–481. doi: 10.1007/s10640-017-0207-7

Newman, J., and Moller, H. (2005). Use of matauranga (Māori traditional knowledge) and science to guide a seabird harvest: getting the best of both worlds? *Senri Ethnol. Studies* 67, 303–321.

Nõges, P., Argillier, C., Borja, Á, Garmendia, J. M., Hanganu, J., Kodeš, V., et al. (2016). Quantified biotic and abiotic responses to multiple stress in freshwater, marine and ground waters. *Sci. Total Environ.* 540, 43–52. doi: 10.1016/j.scitotenv.2015.06.045

Ogilvie, S., Major, R., McCarthy, A., Paine, G., Paine, R., Connor, G., et al. (2018). Mātauranga māori driving innovation in the New Zealand scampi fishery. *N. Z. J. Mar. Freshw. Res.* 52, 590–602. doi: 10.1080/00288330.2018.1532441

Parrado-Rosselli, A. (2007). A collaborative research process studying fruit availability and seed dispersal within an indigenous community in the middle Caqueta River region, Colombian Amazon. *Ecol. Soc.* 12:39.

Patrício, J., Little, S., Mazik, K., Papadopoulou, N. K., Smith, C., Teixeira, H., et al. (2016). European marine biodiversity monitoring networks: strengths, weaknesses, opportunities and threats. *Front. Mar. Sci.* 3:161. doi: 10.3389/fmars.2016.00161

Pelletier, N., Klinger, D. H., Sims, N. A., Yoshioka, J. R., and Kittinger, J. N. (2018). Nutritional attributes, substitutability, scalability, and environmental intensity of an illustrative subset of current and future protein sources for aquaculture feeds: joint consideration of potential synergies and trade-offs. *Environ. sci. technol.* 52, 5532–5544. doi: 10.1021/acs.est.7b05468

Pereira, H. M., Ferrier, S., Walters, M., Geller, G. N., Jongman, R. H. G., Scholes, R. J., et al. (2013). Essential biodiversity variables. *Science* 339, 277–278.

Pettorelli, N., Safi, K., and Turner, W. (2014). Satellite remote sensing, biodiversity research and conservation of the future. *Philos. trans. R. Soc. Lond. B. Biol. sci.* 369:20130190.

Piroddi, C., Teixeira, H., Lynam, C. P., Smith, C., Alvarez, M. C., Mazik, K., et al. (2015). Using ecological models to assess ecosystem status in support of the european marine strategy framework directive. *Ecol. Indic.* 58, 175–191. doi: 10.1016/j.ecolind.2015.05.037

Proctor, R., Gorringe, P., and Roberts, K. (2010). "Australian Ocean Data Network (AODN) "Publicly Funded Data, Publicly Available"," in *Proceedings of the 2010 IEEE 6th International Conference on e-Science*, (Brisbane, QLD: IEEE), 95–101.

Robb, M., Harmsworth, G., and Awatere, S. (2015). *Māori Values and Perspectives to Inform Collaborative Processes And Planning For Freshwater Management (Prepared for Ministry of Business Innovation and Employment and VMO Regional Council Forum)*. Wellington: Landcare Research Manaaki Whenua.

Rohe, J. R., Aswani, S., Schlüter, A., and Ferse, S. C. (2017). Multiple drivers of local (non-) compliance in community-based marine resource management: case studies from the south pacific. *Front. Mar. Sci.* 4:172. doi: 10.3389/fmars.2017.00172

Rout, M., Reid, J., Bodwitch, H., Gillies, A., Lythberg, B., Hikuroa, D., et al. (2018). *Māori Marine Economy: A Review of Literature Concerning the Historical and Contemporary Structure of the Mäori Marine Economy*, 1st Edn. Palmerston North: Massey University.

Schatz, V. J. (2016). Combating illegal fishing in the exclusive economic zone-flag state obligations in the context of the primary responsibility in the coastal state. *Goettingen J. Int'l L.* 7, 383–414.

Smith, L. T. (2012). *Decolonizing Methodologies: Research and Indigenous Peoples*. Dunedin: Otago University Press, 240.

Solan, M., Germano, J. D., Rhoads, D. C., Smith, C., Michaud, E., Parry, D., et al. (2003). Towards a greater understanding of pattern, scale and process in marine benthic systems: a picture is worth a thousand worms. *J. exp. mar. biol. ecol.* 285, 313–338. doi: 10.1016/s0022-0981(02)00535-x

Statistics Canada (2018). *Quarterly Demographic Estimates April to June 2018*. Available at: https://www150.statcan.gc.ca/n1/en/catalogue/91-002-X2018002 (accessed March 12, 20 and May 29, 2019).

Stoner, A. W., Ryer, C. H., Parker, S. J., Auster, P. J., and Wakefield, W. W. (2008). Evaluating the role of fish behavior in surveys conducted with underwater vehicles. *Can. J. Fish. Aquat. Sci.* 65, 1230–1243. doi: 10.1139/f08-032

Tallis, H., Mooney, H., Andelman, S., Balvanera, P., Cramer, W., Karp, D., et al. (2012). A global system for a monitoring ecosystem service change. *Bioscience* 62, 977–986.

Tau, S. (2006). *Iwi Leaders Forum. Iwi Chairs Hui – Wellington 2-4th March 2006*. Available at: http://www.option4.co.nz/Fish_Forums/documents/IwiChairsHuiTauspeech306.pdf (accessed November 15, 2016).

Tawharau o nga Hapū o Whakatohea Iwi Management Plan (1993). *The Investors Guide to the New Zealand Seafood Industry 2017*. Coriolis: MBIE.

Turner, W., Spector, S., Gardiner, N., Fladeland, M., Sterling, E., and Steininger, M. (2003). Remote sensing for biodiversity science and conservation. *Trends ecol. evol.* 18, 306–314.

Uchida, E., Uchida, H., Lee, J. S., Ryu, J. G., and Kim, D. Y. (2012). TURFs and clubs: empirical evidence of the effect of self-governance on profitability in South Korea's inshore (maul) fisheries. *Environ. Dev. Econ.* 17, 41–65. doi: 10.1017/s1355770x11000246

Walters, C. J., and Holling, C. S. (1990). Large-scale management experiments and learning by doing. *Ecology* 71, 2060–2068. doi: 10.2307/1938620

Wilen, J. E., Cancino, J., and Uchida, H. (2012). The economics of territorial use rights fisheries, or TURFs. *Rev. Environ. Econ. Policy* 6, 237–257. doi: 10.1093/reep/res012

Worm, B., Barbier, E. B., Beaumont, N., Duffy, J. E., Folke, C., Halpern, B. S., et al. (2006). Impacts of biodiversity loss on ocean ecosystem services. *Science* 314, 787–790.

Yagi, N., Clark, M. L., Anderson, L. G., Arnason, R., and Metzner, R. (2012). Applicability of individual transferable quotas (ITQs) in Japanese fisheries: a comparison of rights-based fisheries management in Iceland, Japan, and United States. *Mar. Policy* 36, 241–245. doi: 10.1016/j.marpol.2011.05.011

Zeller, D., Booth, S., and Pauly, D. (2006). Fisheries contributions to the gross domestic product: underestimating small-scale fisheries in the Pacific. *Mar. Resour. Econ.* 21, 355–374. doi: 10.1086/mre.21.4.42629521

Zeppilli, D., Pusceddu, A., Trincardi, F., and Danovaro, R. (2016). Seafloor heterogeneity influences the biodiversity–ecosystem functioning relationships in the deep sea. *Sci rep.* 6:26352. doi: 10.1038/srep26352

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A Global Plankton Diversity Monitoring Program

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Plankton are the base of marine food webs, essential to sustaining fisheries and other marine life. Continuous Plankton Recorders (CPRs) have sampled plankton for decades in both hemispheres and several regional seas. CPR research has been integral to advancing understanding of plankton dynamics and informing policy and management decisions. We describe how the CPR can contribute to global plankton diversity monitoring, being cost-effective over large scales and providing taxonomically resolved data. At OceanObs09 an integrated network of regional CPR surveys was envisaged and in 2011 the existing surveys formed the Global Alliance of CPR Surveys (GACS). GACS first focused on strengthening the dataset by identifying and documenting CPR best practices, delivering training workshops, and developing an integrated database. This resulted in the initiation of new surveys and manuals that enable regional surveys to be standardized and integrated. GACS is not yet global, but it could be expanded into the remaining oceans; tropical and Arctic regions are a priority for survey expansion. The capacity building groundwork is done, but funding is required to implement the GACS vision of a global plankton sampling program that supports decision-making for the scientific and policy communities. A key step is an analysis to optimize the global sampling design. Further developments include expanding the CPR for multidisciplinary measurements via additional sensors, thus maximizing the ship-of-opportunity platform. For example, defining pelagic ecoregions based on plankton and ancillary data could support high seas Marine Protected Area design. Fulfillment of Aichi Target 15, the United Nation's Sustainable Development Goals, and delivering the Essential Ocean Variables and Essential Biodiversity Variables that the Global Ocean Observing System and Group on Earth Observation's Biodiversity Observation Network have, respectively, defined requires the taxonomic resolution, spatial scale and time-series data that the CPR approach provides. Synergies with global networks exploiting satellite data and other plankton sensors could be explored, realizing the Survey's capacity to validate earth observation data and to ground-truth emerging plankton observing platforms. This is required for a fully integrated ocean observing system that can understand global ocean dynamics to inform sustainable marine decision-making.

Keywords: Continuous Plankton Recorder, zooplankton, phytoplankton, global monitoring, biodiversity, ocean observing, essential ocean variables

THE NEED FOR GLOBAL PLANKTON OBSERVATIONS

The pelagic zone is the largest biome on Earth. Plankton are found throughout the ~1 billion km^3 of living space in the pelagic zone, and are extremely abundant; one group, the copepods, could be three orders of magnitude more abundant than insects (Schminke, 2007). Plankton underpin almost all marine food webs and provide the link between the physical environment and the fish, marine birds and mammals that society values and which forms the basis of much of the blue economy. Furthermore, plankton are responsible for ~46% of the planetary photosynthesis, the first step in a series of complex biogeochemical processes in the ocean that make up the biological pump, which involves the export of carbon and other elements from the atmosphere via surface waters into the ocean's interior. The many and varied roles of plankton make them essential candidates for measuring the health of our oceans in the Anthropocene.

There is an increasing emphasis on globally coordinated marine science strategies toward "conserving and sustainably using the oceans, seas and marine resources for sustainable development" as laid out in the United Nation's sustainable development goal 14 (SDG14). Plankton are an ideal indicator for sustainably managing our oceans, as they are sensitive to the environment and they are not yet fished to any great extent, meaning that measured changes in plankton communities unambiguously reflect environmental changes and not the amount of harvesting, which complicates analyses of fish stock data.

Plankton: An Essential Ocean and Biodiversity Variable

The Global Ocean Observing System (GOOS) advocates for sustained observations that describe the current ocean state. The initial focus on physical oceanography now informs weather and climate forecasts through a suite of observing platforms (e.g., moorings, voluntary observing ships, satellites, and Argo) to measure the temperature and salinity of the oceans. A more recent focus has been on the biological properties of the ocean, developed from the Framework for Ocean Observation (Lindstrom et al., 2012), with GOOS establishing a Biology and Ecosystems Panel in 2015. Its remit is to promote a global, sustained, and targeted ecosystem observing program based on essential ocean variables (EOVs). Plankton (abundance and diversity) were identified as EOVs with moderate to high relative impact for addressing societal drivers and pressures (Miloslavich et al., 2018).

The Group on Earth Observations Biodiversity Observation Network (GEO BON) has developed Essential Biodiversity Variables (EBVs) to "play the role of brokers between monitoring initiatives and decision makers" with a focus on the status and trend in biodiversity. EBVs include taxonomic diversity to inform policy makers on community composition and secondary productivity as well as plankton functional type variables to inform on ecosystem structure and function.

A key challenge in observing plankton in the pelagic zone over the vast expanses of the ocean is to estimate the zooplankton component. For nearly four decades, phytoplankton have been observed from space. Satellites not only provide estimates of phytoplankton biomass (chlorophyll-a), but also of some phytoplankton functional types (Brewin et al., 2010), although phytoplankton species composition remains elusive. However, zooplankton, the intermediate trophic link between phytoplankton and fish, cannot be observed from satellites. Zooplankton can readily be monitored over local scales using nets and modern imaging and laser systems, but sampling zooplankton over large spatial scales – both abundance and species composition – remains challenging.

Continuous Plankton Recorder Surveys

First routinely deployed in 1931 the Continuous Plankton Recorder (CPR) survey is the longest running, most extensive, marine biological sampling program (Richardson et al., 2006). Uniquely, the CPR collects *in situ* samples over large spatial scales, allowing species-level identification of plankton composition and abundance. This is possible because the CPR is sufficiently robust to be deployed from commercial ships (ships of opportunity), unaccompanied by researchers, making sample collection cost-efficient over large ocean tracts, although the species-level identification currently necessitates relatively high processing costs per sample. Full technical details of the CPR can be found in Batten et al. (2003a).

The first CPR sampling took place in the North Sea in 1931, followed by a network of transects around the United Kingdom which extended over the European shelf by the late 1940s. Further expansion to the western North Atlantic occurred next, followed by the first independent regional survey in 1961 off the east coast of the United States. Over time, additional regional surveys have extended CPR operations to northern and southern hemispheres, the North Atlantic and Pacific Oceans as well as smaller regional seas (**Figure 1**).

Strengths and limitations of CPR sampling are well documented in the CPR literature (e.g., Richardson et al., 2006) and will not be repeated here but its specifications

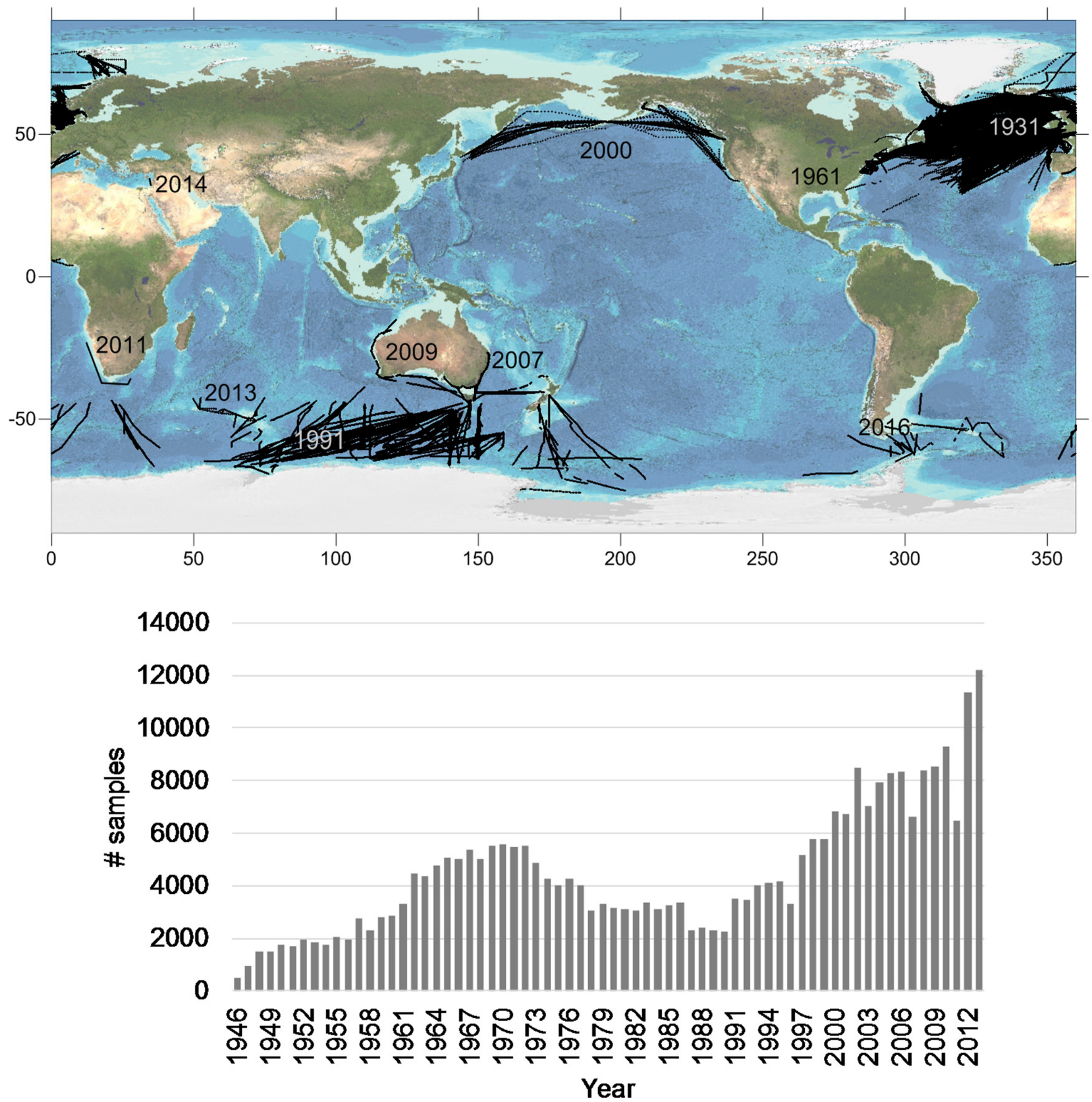

FIGURE 1 | Upper panel shows the CPR transect locations together with the year of inception of that local survey. Lower panel shows the combined total number of CPR samples that have had plankton counts determined.

mean that only a portion of the entire plankton community is sampled, a fact that is common to all plankton sampling strategies (Wiebe and Benfield, 2003). The CPR filters plankton from the seawater using a mesh with a nominal size of 270 µm [although because of the silk weave it commonly captures phytoplankton down to ~10 µm (Richardson et al., 2006)]. The seawater entrance aperture has sides of 1.2 cm. There are, therefore, upper and lower size limits of organisms that can be effectively captured and retained. The preservative used is formaldehyde which works well for some species, but not for others. The high speed of sampling (up to 25 knots) means that fragile and gelatinous groups are often damaged or destroyed. The CPR is towed at a fixed near-surface depth (5–10 m) meaning it only captures those taxa that spend some of their time in the mixed layer. Despite these limitations the sampler has changed relatively little since its inception and is internally consistent. Many hundreds of taxa are routinely identified from CPR samples, resulting in a rich ecological dataset of unparalleled spatial extent allowing the identification of changes in plankton communities over large space and time scales, such as multi-decadal and ocean basin. There is a diverse scientific literature based on these data of over 1,000 peer-reviewed publications (a selection is presented in **Table 1**). It should also be noted that the CPR is not an appropriate sampler for very shallow, near-shore regions, where transect lengths are less than about 100 km or for station-based sampling. However, through collaborative approaches suggested in section "The Future," CPR data could

TABLE 1 | A selection of publications using CPR data to demonstrate the breadth of applications.

Subject	Area/Timeframe	Main results	References
Pollution	Irish Sea 1996 vs. long-term	After the Sea Empress oil spill, a shift in zooplankton community composition and a decrease in population spawning was observed when comparing long term to post spill data.	Batten et al., 1998
Pollution	North Sea, North Atlantic 1960s–1990s	An increase of microplastics toward the end of the previous century was recorded from CPR samples, with oceanic areas having less microplastics than closed systems.	Thompson et al., 2004
Bio-accumulation/pollution	Northwest Atlantic	Methylmercury (MeHg), a harmful neurotoxin, concentrations as modeled from CPR phytoplankton data, predict that climate change forcing will have a profound effect in methylmercury concentrations and linear increases across trophic groups.	Schartup et al., 2018
Alien species dispersal	English Channel to North–East Atlantic	*Coscinodiscus wailesii,* is a non-indigenous diatom, with detrimental effects to fish populations around the United Kingdom[1]. The survey tracks its appearance, dispersal, subsequent establishment as well as assesses and defines its interaction within the communities[2].	[1]Boalch and Harbour, 1977; [2]Edwards et al., 2001
Fisheries	Bering Sea 2000–2014	A 15 years CPR dataset revealed alternating patterns of zooplankton and phytoplankton abundances to be linked to the biennial Pink Salmon class strength. The evidence of a trophic cascade may be used as a predictor for future population trends.	Batten et al., 2018
Fisheries	North Sea 1948–1997	Unsustainable fishing practices and the subsequent 1977–1982 ban on herring fishing[3] is reflected in changes within the planktonic community. The findings support the importance of top down regulation effect to ecosystem changes in complex ecosystems[4].	[3]Koslow, 1983; [4]Reid et al., 2000
Fisheries	1951–2005 North Atlantic, North Sea	Blue-whiting spawning seems to be induced by a narrow window of conditions suggested to be optimal for the survival of the larvae (mainly salinity between 35.3 and 35.5 psu). Predictive tools and CPR data could be used to map spawning distribution.	Miesner and Payne, 2018
Fisheries	North Sea 1958–1999	Plankton composition changes in 1980's induced a decrease in cod populations. More importantly, abundance and diversity of the plankton community in any given year was found to be linked to next year's cod stock.	Beaugrand et al., 2003
Harmful Algal Blooms	North Atlantic, North Sea 1958–2004	Increasing temperatures are contributing to the increased frequency of the harmful algal blooms according to this study. A stepwise regime shift in the appearance and composition was also noted late 1988 with a high intensity of increasing HABs.	Edwards et al., 2006
Climate Change	[1]North Atlantic 1960–2010 [2]North Sea, North Atlantic 1962–1992	The study of cold-water *Calanus finmarchicus* and warm water *Calanus helgolandicus* indicates ecological adaptations to climate change with implications to fisheries catches. The species have adjusted their geographical distribution toward respective optimal temperatures[5], while temporal investigation, shows *C. finmarchi*cus peaks in May, and *C. helgolandicus* peaks twice with the highest peak being in September[6].	[6]Planque and Fromentin, 1996; [5]Hinder et al., 2014
Climate change	North Sea, North Atlantic 1960–1999	Community composition reflects plankton responses to the NAO and the increasing temperature regime, with associations of warm-water copepods expanding to the north.	Beaugrand et al., 2002
Climate change	North Sea North Atlantic 1958–2002	The study shows severe warming of 0.5°C in southern regions. Warming of waters coincides with phytoplankton abundance decreases which in turn create a cascading effect to zooplankton grazers and higher trophic groups.	Richardson and Schoeman, 2004
Pathogens/human health	North Atlantic and North Sea 1958–2011	The increase of environmentally transmitted Vibrio infections is linked to blooms of marine Vibrio, whose presence was genetically determined on CPR samples. The study stipulates rising temperatures could also increase Vibrio outbreak frequency.	Vezzulli et al., 2016
Human health	Labrador Sea, North Atlantic, North Sea 1970–2011	Genetic evaluation of archived CPR samples identified the long-term presence of antibiotic resistance genes in marine plankton.	Di Cesare et al., 2018
Pathogens	Tasman Sea 2009	The pathogen, *Aspergillus sydowii*, was genetically identified from CPR samples after a dust storm event, fungal cultures and field data of *A. sydowii* had adverse effects on mobility of the coral symbiont, Symbiodinium.	Hallegraeff et al., 2014
Policy and management	Northeast Atlantic 1958–2017	Policy indicators at multiple taxonomic scales were developed to formally assess pelagic habitat biodiversity under the EU Marine Strategy Framework Directive. As a suite, the indicators inform on anthropogenically driven change as well as changes caused by prevailing environmental conditions.	McQuatters-Gollop et al., 2015, 2017; Bedford et al., 2018
Eutrophication	North Sea 1958–2004	A new quantitative dataset created by integrating CPR and remotely sensed chlorophyll data suggested that eutrophication is a local, coastal issue in the North Sea and climate change is the primary driver of increased productivity. Increasing water clarity and higher sea surface temperature has resulted in a longer growing season in coastal waters which are consequently now more sensitive to nutrient input.	McQuatters-Gollop et al., 2007
Model assessment	North Atlantic, Australia	As biogeochemical and ecosystem models are increasingly used in marine management, CPR data are being used for model assessment. This is particularly true of Zooplankton data, which are not available from satellites.	Lewis et al., 2006; Skerratt et al., 2019
Ecosystem assessments		Plankton indicators from the CPR are used in regional, national and international ecosystem assessments to describe the state and trends of marine systems.	Evans et al., 2016

provide larger scale context or link distant sampling locations where other samplers are used.

Initiating the Global Alliance of CPR Surveys

At the 2009 Global Ocean Ecosystem Dynamics (GLOBEC) Open Science Meeting in Victoria, Canada, CPR users from regional surveys met to examine new results and to begin discussions on stronger links between surveys and how it may be possible to integrate their products (Batten and Burkill, 2010). Two years later, in September 2011, the Global Alliance of CPR surveys (GACS) had its first meeting and signed a Memorandum of Understanding to work toward providing an integrated data set derived from the several national CPR Surveys that currently operated or were planned in the near future. It was anticipated that each of these surveys would continue to operate independently but with increasing emphasis for their contribution to the global perspective. There were six objectives that were laid out as targets;

(1) A common aim "to understand changes in plankton biodiversity at ocean basin scales through a global alliance of CPR Surveys".
(2) Adoption of common standards and procedures wherever possible.
(3) The generation of a plankton biodiversity database that would ultimately be made freely available to the science community.
(4) The setting up of a website for publicity and data access.
(5) The production of a regular Ecological Status Report on Global Plankton Biodiversity.
(6) An interface between plankton biodiversity and other global ocean observation programs.

CURRENT STATUS: SUCCESSES AND STUMBLING BLOCKS

Nine independent regional CPR surveys currently exist which are members of GACS (**Figure 1**, upper panel). One survey has ceased operation since GACS was formed (the east coast of the United States) but some sampling has been maintained there by the United Kingdom CPR survey. The proportion of collected samples that are analyzed for taxonomic abundance differs between surveys but the lower panel of **Figure 1** shows the annual total of analyzed samples, globally, to the year when all surveys have reported data. Samples that are collected but not analyzed are for the most part archived and can be used for additional studies. The total of collected and archived samples is about twice the number shown in **Figure 1**.

Many of the surveys have started relatively recently; however, there are now almost two decades with more than 5,000 analyzed samples per year that are spread over at least 3 regions (regional seas or ocean basins) and both hemispheres. Funding is the largest limitation to further expansion of CPR surveys; there is strong competition for available funds and there is a (false) perception that it takes many years to realize the benefits of a new CPR survey. There are many issues apart from long-term changes that can be addressed by young CPR surveys (see section "The Diversity of Applications of CPR Data" for examples). CPR surveys that have ceased operation have done so not because of lack of scientific merit, but because of a paucity of funding.

Resources have also limited the speed at which the global CPR database has been developed. Building the infrastructure to link the regional surveys relies not just on physical hardware and person-time in the GACS host institution but also person-time and expertise at each regional survey to format and deliver the data, some of which consist of only one Principal Investigator with many competing requirements for their time. While the benefits to participating in GACS and contributing to a global system are clear to all the scientists involved it is nonetheless not a small task for most to isolate resources for this process when the funding source may have an entirely national or regional focus. Creation of the CPR global database is a significant step for marine ecology as the only other plankton data at a similar spatial scale is currently from remote sensing. Although satellite data have global ocean coverage, they can only provide information on phytoplankton biomass and a few key functional groups, and cannot be used to examine oceanic or trans-oceanic changes in species and, therefore, biodiversity. Once the global CPR database is fully developed it can be interrogated to support integrated global analyses of CPR data, furthering understanding of near-global scale plankton dynamics and of inter-regional connectivity of pelagic habitats.

Defining Best Practices, Capacity Building and New Surveys

Continuous Plankton Recorder surveys share many methodological similarities. These include the CPR device itself [the same design is used by all surveys except the Southern Ocean (SO) surveys, which use a slightly modified version for deployment in sea ice], the silk mesh for capturing plankton (all sourced from the parent organization), and methods for phytoplankton counting [see Richardson et al. (2006) for details]. New surveys, however, are not constrained by maintaining the consistency of a time series and can modify the methods to better address their primary research questions. For example, surveys have different frequencies of deployment and this is not only related to cost: some surveys (e.g., in the North Atlantic) tow monthly to address questions concerning phenology and succession in temperate/polar regions, while other surveys e.g., Australian CPR survey (AusCPR) tow every 3 months in (less seasonal) tropical regions to address inter-annual variation. Another difference among surveys is the method of zooplankton counting: some surveys in (diverse) tropical regions wash the plankton off the mesh for identification of taxa to a higher taxonomic level because the focus is on changes in diversity with climate change (e.g., AusCPR) or to avoid the need for a purpose-built microscope (e.g., New Zealand CPR and SO-CPR), while other surveys complete on-mesh analysis (which is more challenging for species-level identification of smaller species) that is well-suited to the larger organisms and lower diversity of temperate regions (e.g., the North Atlantic). Therefore, surveys in different regions have bespoke research questions, and thus some of the detailed methodology has been modified accordingly, precluding the use of identical methods across all surveys. However, these methodological differences can be viewed as being akin to measuring temperature in the ocean on different platforms (e.g., satellites, moorings, XBTs, or Argo floats) at different spatial and temporal resolutions – each platform by itself is useful for answering specific questions, but their data can be successfully integrated into global temperature products. The similarity of the same sampling device – the CPR – and the species-level plankton identification – are key to the comparability of the data. This comes with some caveats though, as abundances from the CPR are semi-quantitative, providing consistent information on spatial and temporal variation, but not on absolute abundance, which is usually better measured with other sampling techniques (Clark et al., 2001; John et al., 2001; Batten et al., 2003a; Richardson et al., 2004, 2006; Lewis et al., 2006).

An early focus of GACS has been to prepare manuals and materials to document the standard procedures used in all aspects of CPR deployment, maintenance and sample processing and archiving by the North Atlantic survey at the Marine Biological Association, United Kingdom [now home to the former Sir Alister Hardy Foundation for Ocean Science (SAHFOS) that also hosts GACS]. Technicians from several nations that have subsequently initiated new surveys have attended training courses held by the North Atlantic survey. A short-term goal is to make those documents accessible to all through the Ocean Best Practices Repository.

The Diversity of Applications of CPR Data

Continuous Plankton Recorder data have been used to study a multitude of scientific and societal questions (**Table 1**). The assessment of global issues such as climate change (e.g., Hinder et al., 2014) and fisheries (e.g., Batten et al., 2018) provide the means to recognize similar trends in different areas. The survey has also been successful in evaluating regional stressors (e.g., Vezzulli et al., 2016) or distinct events with globally applicable results or methodologies (Hallegraeff et al., 2014). Here (**Table 1**) we do not aim to provide an exhaustive list of the CPR bibliography but rather a sample of the breadth and depth of knowledge produced through the various surveys.

Review of the Different Funding Models

Historically, the major challenge facing sustained ocean observing programs is to attract long-term funding (Duarte et al., 2009; Koslow and Couture, 2013). Physical oceanographic components of GOOS have been funded by national governments rather than by international organizations such as the UN or World Bank, and this has also been the case for CPR surveys. CPR surveys have a range of successful funding models, but the most common is some type of funding by national governments through a dedicated program, supplemented by competitive grants and industry collaboration. One successful funding model within Australia has been for the small biological observing community to team up with the physical oceanographic observing community to push for a large and integrated observing system. Thus the Integrated Marine Observing System (IMOS) was born, with ∼\$US 11 million per year from the Australian Government and \$US14 million per year in matching co-investment (Hill et al., 2010; Moltmann, 2011). All platforms, from physical to biological, have benefitted from being part of a larger integrated and coordinated system, allowing more direct lines of communication and influence with government. The disadvantage is that this single funding source means the program is vulnerable to fluctuating Government budgets.

Another successful model has been industry collaboration. Individual routes in some surveys are supported by the oil and gas industry, in proactive collaborations. For example, British Petroleum has funded an AusCPR route across the Great Australian Bight in southern Australia – a region of developing oil and gas interests – to establish environmental baselines and understand ecosystem connectivity. In the North Atlantic, the CPR route from Aberdeen to the Shetland Islands is funded by the oil and gas exploration company Nexen because it passes close to their drilling platform. Arguably the most challenging pot of money to access is that of national competitive grants, but this has provided additional funding for specific hypothesis-driven research such as work on marine fungal blooms (Australian Research Council funding) and viruses in CPR samples (United Kingdom Natural Environmental Research Council). The North Pacific CPR Survey has been partially funded by the Exxon Valdez Oil Spill (EVOS) program for the past 16 years. This has provided sustained funding toward a North–South route along the United States and Canadian west coasts. Although large-scale environmental disasters are thankfully rare, they do sometimes provide the opportunity for initiating long-term ocean observation. Supplemented by funding from the North Pacific Research Board and the Canadian Government's Department of Fisheries and Oceans through a consortium the North Pacific Survey has maintained two lengthy transects (including a *trans*-Pacific route) for 19 years.

It is clear there is no single best way to fund CPR surveys, but having close links with the national research community involved in ocean observation, being responsive to short-term local funding priorities, and partnering with industry have all been fruitful approaches for long-term sustained funding.

The First CPR-Based Ecological Status Reports

The translation of scientific jargon into non-technical language is an important challenge in disseminating scientific results to policy makers. An important driver behind the North Atlantic survey's strategy was to transfer scientific information revealed by CPR data to decision makers in an accessible and useful format. To address this challenge, in the early 2000's the CPR program (Sir Alister Hardy Foundation for Ocean Science Annual Report, 2002) published its first annual Ecological Status Report. The Ecological Status Reports apply an indicator approach to summarize the status of North Atlantic plankton using data and research from the CPR survey. The indicators were initially developed to monitor annual changes in key attributes of planktonic systems with a particular emphasis on indicators that were relevant to evolving United Kingdom policy and marine ecosystem management. This strategy of using indicators to clearly communicate the relevance of the CPR was particularly important to the funders of the North Atlantic CPR Survey such as the United Kingdom's Department of Environment, Food, and Rural Affairs (Defra). Defra continue to be the major funder of the North Atlantic CPR survey, with CPR data and science integral to informing United Kingdom and EU policy (see also policy section, "CPR-Derived Metrics in Marine Policy").

Marine management drivers continue to influence research using CPR Survey data. Management and policy drivers have co-evolved with the survey, from purely a fisheries perspective in the 1940s to a whole ecosystem approach to management in the 21st century (Edwards et al., 2010). This close alignment with management and policy needs and the continued relevance of the CPR survey in providing large-scale evidence of marine ecosystem and anthropogenic changes (**Figure 2**) is one of the reasons why the North Atlantic CPR Survey has survived for 80 years, when many time-series have not lasted more than a decade (Koslow and Couture, 2013). CPR data (as summary metrics) from several regional surveys have also contributed to the International Group for Marine Ecological Time Series (IGMETS) report. An ongoing effort, this presents an analysis and overview of oceanic trends based on a collection of over 340 *in situ* marine ecological time series[1], and supplemented with satellite-based spatio-temporal SST and chlorophyll background fields (UNESCO, 2017).

Since the formation of GACS in 2011 the CPR Ecological Status Reports have been used to report on changes by all the CPR regional surveys and give the international community a global perspective on plankton community change (Edwards et al., 2016). These Global Ecological Status Reports maintain the indicator approach, quantifying marine climate change impacts (biogeographical shifts and phenology), changes in ecosystem health (water quality and marine pathogens), changes in ecosystem state (biodiversity and invasive species). They continue to evolve and adopt new indicators, such as ocean acidification and marine microplastics, as new anthropogenic issues emerge (Edwards et al., 2016). Looking to the future, the Global Ecological Status Reports will be used to report metrics to global initiatives such as the EOVs and EBVs for GOOS, the marine component of GEO BON (MBON, Marine Biodiversity Observation Network) and the IPCC. They also support the recent recommendations made by G7 Ministers of Science which include to "Support an enhanced system of ocean assessment through the UN Regular Process for Global Reporting and Assessment of the State of the Marine Environment that would help develop a consensus view on the state of the oceans on a regular timescale." This would in turn enable sustainable management strategies to be developed and implemented across the G7 group and beyond.

[1]https://igmets.net/report

CPR-Derived Metrics in Marine Policy

The CPR Survey has co-evolved with policy drivers and through the Survey's development of policy-relevant applied indicators, the CPR has played an integral part in providing relevant, targeted evidence for United Kingdom, European and international decision-makers (Edwards et al., 2010). While CPR data and science have contributed to national ecosystem state assessments in the United Kingdom (United Kingdom Marine Monitoring, and Assessment Strategy [Ukmmas], 2010), United States (e.g., Zador and Yasumiishi, 2017), Canada (Chandler et al., 2017), and Australia (Richardson et al., 2015; Evans et al., 2016), the survey's transboundary nature has enabled it to play a key role in supporting regional policy and management initiatives. The European Union's Marine Strategy Framework Directive (MSFD) takes an ecosystem approach to achieving Good Environmental Status in Europe's regional seas. Uniquely, the CPR survey's pan-European nature supports collection of plankton data at this regional scale. CPR data were, therefore, fundamental to the conception, development, and delivery of two Northeast Atlantic-wide pelagic habitats indicators for the EU's Marine Strategy Framework Directive (OSPAR, 2017). The first indicator uses plankton functional groups, or lifeforms, to reveal change in plankton communities while the second uses the Phytoplankton Colour Index and total copepod abundance to assess changes in plankton biomass and abundance (McQuatters-Gollop et al., 2015). Both indicators are dependent on the taxonomic data collected by the CPR, with the underlying genus- and species-level information integral to interpreting indicator change to inform a program of management measures in the United Kingdom and the OSPAR (Northeast Atlantic Regional Seas Commission) region (McQuatters-Gollop et al., 2017).

Another example of a CPR survey's contribution to regional decision-making is through the SCAR Southern Ocean CPR survey (SO-CPR), which is the major zooplankton monitoring program in the Antarctic region and supports the management of Antarctic biodiversity and resources. The SO-CPR survey includes members from Australia, Japan, Germany, New Zealand, France, South Africa, Brazil, Chile, United Kingdom, United States and Russia and, as of 2018, has collected over 250,000 nautical miles of zooplankton samples (see Hosie et al., 2014, and the SO-CPR Database metadata record at Australian Antarctic Data Center[2]). The Survey provides data and advice for use by the general Antarctic research community, notably via the Scientific Committee on Antarctic Research (SCAR) as well as to national and intergovernmental organizations within the Antarctic Treaty System such as the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), the Committee on Environmental Protection (CEP), the Southern Ocean Observing System (SOOS), the Monitoring program of the Japanese Antarctic Research Expedition (JARE); and the Ministry for Primary Industries project of New Zealand (Robinson et al., 2014).

The extensive spatial scale, multi-decadal time-series, and taxonomic richness of the CPR survey have placed CPR science

[2]https://data.aad.gov.au/metadata/records/AADC-00099

1. Societal drivers

Sustainable economic growth/development
Conservation/ biodiversity
Improved management/ ecosystem approach
Capacity building and technology transfer
Food security - fishing/aquaculture
Environmental quality and health
Energy production

2. Societal pressures

Climate change
Ocean acidification
Extreme weather events
Loss of resources/habitats
Overfishing
Seabed mining
Solid wastes/ marine litter
Pollution/eutrophication
Invasive species
Coastal development

3. Scientific questions

What is the current status of life and biodiversity in the oceans?
How is life in the oceans changing?
What are the natural and anthropogenic drivers of change?
Are HAB events increasing in frequency or spatial location?
Are invasive species increasing?
How does the changing life in the oceans affect ecosystem function (health and services)?

4. Biological phenomena to capture

Phenology
Occurrance of Harmful Algal Blooms (HABs)
Biogeographical shifts
Biodiversity/invasive species
Impact on calcareous organsims
Ecological regime shifts
Ocean productivity
Carbon sequestration

5. Spatial and temporal scale of biological phenomena

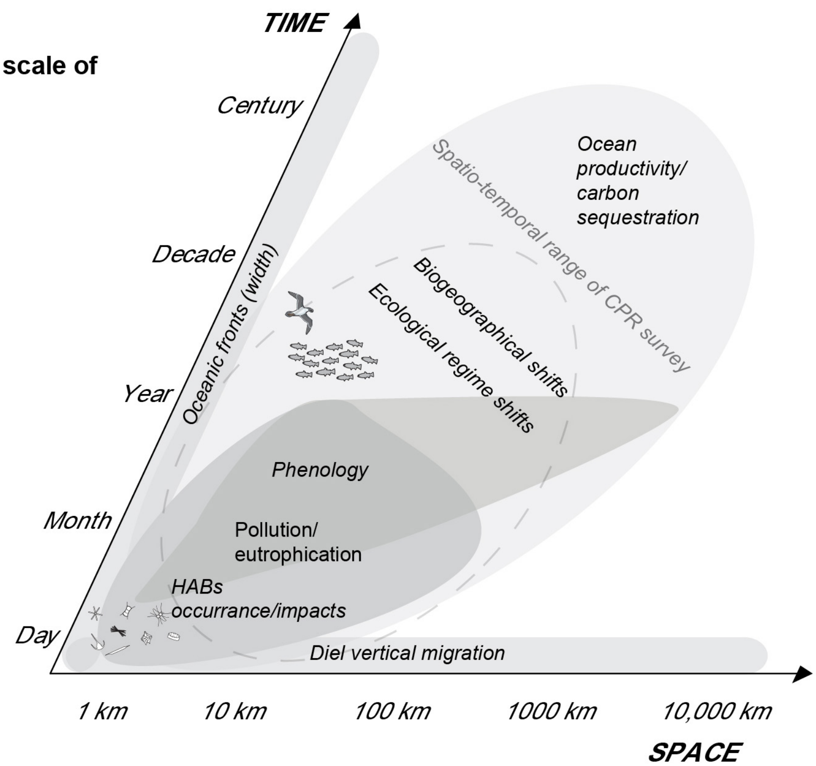

FIGURE 2 | Key societal drivers and pressures on the marine environment and the aspects of plankton dynamics used to capture their impacts on the oceans. The aspects of plankton dynamics addressed occur at multiple spatial and temporal scales and therefore require monitoring by a system, such as the CPR survey network, which operates at similar scales. Based on Edwards et al. (2010).

at the forefront of evidence provision for high-level policy and management advice. Data and research from the survey have informed high profile and strategic global marine assessments such as the IPCC status reports (Pörtner et al., 2014) and the United Nations World Ocean Assessment (Innes et al., 2016). These international assessments are key to raising the profile of marine ecosystem change and are widely read by those on both sides of the science-policy interface. Integrating and analyzing data holistically across the GACS network through a global database with open access to data products would further increase the global impact of CPR data and research.

Instrumenting the CPR

The CPR surveys are best known for taxonomic plankton data based on microscopy including many phytoplankton, hard-shelled microzooplankton and meso-zooplankton. With the developments in technology that have occurred during its history, most notably in the most recent two decades, there has been a push to add supplemental instrumentation which can also collect oceanographic data. Using the CPR itself as a platform takes full advantage of the sampling infrastructure already in place and can extend the types of data collected, both enhancing the understanding of *in situ* conditions for the plankton communities sampled and maximizing the information that can be gained from having the instrument in the water.

The North Atlantic CPR survey has developed and used a water sampler installed on the CPR body, so far the only automated water sampler that can be deployed on a vessel, external to the ship, whilst still moving. The water samples thus obtained from the English Channel were used to successfully identify planktonic organisms using metagenetic approaches (Stern et al., 2015), revealing a range of unseen diversity not detected by microscopic methods. Additionally, abundance of different size-classes of plankton from flow cytometry analysis of the water samples has been shown to be robust and has revealed new patterns of abundance. Genetic and size-classified biomass data can enhance existing CPR datasets to better model biotic responses to the environment. Alongside a range of "PlankTags" (self-powered instruments that can telemeter data in real-time) and off-the-shelf CTD instruments that measure temperature, salinity and fluorescence, there are a number of biogeochemical sensors that are being tested on the CPR, which can, for example, measure the concentration of carbon dioxide in the seawater.

THE FUTURE

Synergies With Satellite Observations

Continuous Plankton Recorder surveys are the program that can provide basin-scale data similar to satellites, but although the temporal scale is far less frequent, CPRs have the advantage of providing species-level taxonomic data. Studies have been carried out that combine CPR and satellite data. Batten et al. (2003b) and Raitsos et al. (2013) used satellite fluorescence data to positively validate the CPR's Phytoplankton Colour Index, showing that although a simple index, it reveals seasonal and long-term trends in phytoplankton communities. Rêve-Lamarche et al. (2017) used CPR diatom taxonomic data to associate diatom assemblages with specific spectral anomalies (from PHYSAT) for regions of the English Channel and North Sea. The ability to ground-truth satellite-derived phytoplankton functional groups from different regions around the world sampled with CPRs is an attractive idea. Through collaboration with groups such as the International Ocean-Colour Coordinating Group (IOCCG) this is an area that should be further exploited as a short-term goal.

Adding Value to Development of New Sensors and Platforms

There are other simultaneous efforts to improve and extend the measurement of global plankton. The Scientific Committee on Oceanic Research (SCOR) Working Group 154 "Integration of Plankton-Observing Sensor Systems to Existing Global Sampling Programs," for example, is reviewing the current inventory of state-of-the-art, validated, plankton-related measurements and off-the-shelf sensors. This review will identify those that could be implemented/installed on board research vessels that are operating on other globally coordinated ocean monitoring networks (Boss et al., 2018) such as the Global Ocean Shipped-Based Hydrographic Investigations Program (GO-SHIP), http://www.go-ship.org/ and OceanSITES, http://www.oceansites.org/. GOSHIP co-ordinates *trans*-basin ship surveys that are repeated at least once every 10 years per transect (frequency of sampling varies). OceanSITES co-ordinates full ocean depth time series observations from moorings and repeat ship visits. The WG will also identify the required resources to support those measurements, as well as the data-dissemination infrastructure, and make recommendations. The WGs approach is to minimize the impact on these existing sampling programs that do not yet record plankton by using self-contained instrumentation. GACS data will be invaluable in providing links between such new measurements that may be temporally sparse (GO-SHIP) or spatially restricted (OceanSITES) with nearby well-established CPR time series as well as provide an historical context. CPR data also provide the species-level information that is often missing with more automated approaches. Many of the developing autonomous systems (boats, gliders, subs, underway systems etc.) still require a significant amount of person time to set-up, supervise and recover. Emerging plankton observing technologies are quickly developing but are often not (yet) robust enough to operate at vessel speeds of more than a few knots, or be deployed unattended for thousands of kilometers. The time will come when they are ready to complement traditional observation systems, but collaboration between networks is essential if we are to link existing and new time series to fully recognize the magnitude of pelagic ecosystem changes.

Instrumentation and Analyses Achievable in the Next Decade

The CPR Survey has already developed qualitative and quantitative assays for microbial pathogens, harmful algae and overall plankton diversity that can be used for indicator development of water quality and ecosystem health. Additionally, assays have been developed to genetically capture plankton diversity from CPR samples, despite their preservation in formaldehyde, allowing for greater scope to fully detect pelagic biodiversity (e.g., Vezzulli et al., 2016). Using an improved filter-based capture method will allow the sampling of greater water volumes which will improve detection rates of species, together with metagenetic detection methods, would provide a new automated method for rapidly monitoring diversity.

The CPR Survey currently deploys PlankTags on nine routes within the North Sea, English Channel and in the N.E. Atlantic. The next generation PlankTags will be able to measure a greater suite of biogeochemical proxies (Conductivity, Temperature, Depth, Chl-a fluorescence) and are designed for *trans*-oceanic deployment. A methodology for "Macro" FlowCam processing is also being developed in order to explore the size and abundance spectra of zooplankton and plastics from CPR samples (or discrete water samples).

Quantifying the distribution and abundance of plastics within the world ocean has become a necessary demand due to increased concern over potential marine and human health impacts. GACS provides a promising platform to achieve the global coverage required and to develop the CPR protocol further for monitoring large and small plastics that get caught within the CPR. As new technologies capable of identifying the composition of microplastics continue to develop (such as the use of hyper-spectral cameras), these may be able to provide a method to retrospectively analyze historic CPR samples and create a more complete picture and consistent monitoring of the global plastics problem.

Becoming Truly Global

New Surveys to Fill Gaps

A frequently asked question of members of existing CPR surveys is why you would choose to use a CPR when there are many newer plankton samplers in use and under development? The CPR is the method-of-choice for large-scale plankton surveys, which is what is needed for a global program, and no other device currently available delivers similar information at a similar cost. There are four main reasons:

(a) Cost: Research vessel costs for large-scale surveys, (e.g., fisheries surveys) are tens of thousands of dollars a day in most countries. Other than a small gratuity to the crew of the merchant ships, CPR sampling is essentially free. Most current plankton samplers are far too fragile for Ships of Opportunity (SOOP) and require dedicated research ship time, making them far too expensive for long-term, large-scale surveys. While autonomous samplers that can cover reasonably large distances are in the pilot phase (e.g., Ohman et al., 2019) there are still significant start-up, maintenance, and data processing costs. The expense of microscopy required to process CPR samples is offset by the longevity of the instrument. With servicing, the CPR can last decades even when it is deployed monthly on SOOPs and it is highly reliable with a success rate of over 90%. It can also easily be moved between vessels since only a towing point needs to be added, there is no alteration of a ship's water intake system. Many modern instruments require regular calibration and technician time. Longevity, reliability and low-cost sampling make the CPR particularly good value-for-money.

(b) Species-level taxonomy: Most other modern instruments for zooplankton or phytoplankton do not collect species-level taxonomy. No autonomous vehicle can currently identify phytoplankton or zooplankton to species level. Molecular approaches can identify species, but cannot estimate abundance very well, which is relatively easy with microscopy. Molecular approaches also do not distinguish juveniles from adults, and females from males, which is relatively straightforward with microscopy. So, whilst somewhat labor-intensive, the CPR approach provides highly resolved taxonomic data together with abundances. This is essential for effective biodiversity monitoring.

(c) A physical sample: Many other plankton sampling techniques, such as the Video Plankton Recorder, Optical Plankton Counter, autonomous vehicles, and Imaging Flow Cytobot, extract a measure of the plankton community, but do not collect a sample. Having a physical sample, especially when archived and curated, allows for many additional analyses such as molecular studies, other biochemical assays (stable isotope measurement for example), as well as analyses of taxa that were not able to be counted at the time of sample processing. There are very likely new techniques in the future that are not currently imagined that can also be applied to an archive of physical samples.

(d) Comparative analyses: There is an archive of standardized samples and data from other CPR surveys around the globe for comparison with new results. Wiebe and Benfield (2003) reported that there were then over 150 different zooplankton samplers, with no acknowledged global standard other than the CPR. The ability to place a new regions' results into a global context will increase the ability to understand a local system.

For all of these reasons, the CPR is the only reliable, robust sampler that can be used over large space and long-time scales – and remains the method-of-choice for new plankton surveys.

Designing the Sampling

An important current gap in the GACS vision of having a global CPR survey is the sampling design. One way to envision such a design is to consider the different bioregions of the ocean. There are several classification systems in use that define marine biogeochemical provinces for the pelagic realm in terms of major oceanographic and ecological patterns: (a) the Longhurst Biogeochemical Provinces (BGCP; Longhurst, 2007), (b) the Marine Ecoregions of the World (MEOW; Spalding et al., 2007), (c) the Large Marine Ecosystems (LME for coastal systems; Sherman, 2005) which also includes socio-economic factors in the delineations. Adding ecological complexity and dynamics to such essentially static systems by combining satellite data and *in situ* observations has been proposed by Kavanaugh et al. (2016). However, probably the most currently accepted global bio-regionalization for the open ocean sampled by the CPR is the "Longhurst Provinces" (first presented in Longhurst, 1998), which are 56 ecoregions based primarily on the major oceanographic regimes (**Figure 3**). For a global plankton survey, we might aim for a network that covers all of these provinces. Currently, CPRs sample provinces in the North Atlantic (e.g., NECS, NADR, SARC, and NASE), the Southern Ocean (SANT, ANTA, and NEWZ), around Australia (AUSE, AUSW, and TASM), and the North Pacific (CCAL, PSAE, and NPPF). These are relatively well sampled, but most of the biogeographical provinces are not sampled (**Figure 3**), including whole parts of the ocean including the South Pacific (SPSG) and the southern Indian Ocean north of the Southern Ocean (ISSG). Coverage of CPR sampling will continue to grow, but we can stimulate its development by learning from the approach of the physical oceanographic research community to building the global observing system for climate. Beginning in 1997, the community released a blueprint for what the global observing system for ocean climate would look like, detailing the needed temporal and spatial coverage of its major platforms (National Research Council, 1997). Not only was this global system designed through community discussion, but by simulated sampling of temperature and salinity by different platforms from output of hydrographic models. This enabled an objective design of the system, based on the needed precision of the data products. It also provided a target that could be tracked through time – motivating the research community and focusing the attention of funding bodies. For example, the ARGO network, which had only 544 floats in 2002, reached its design specification of 3,000 floats globally in 2007, and has maintained this coverage ever since.

As the physical oceanographic research community used hydrodynamic models that capture the time and space scales of variation in temperature and salinity to design the physical components of GOOS, so the biological oceanographic research community can use global biogeochemical and ecosystem models that incorporate plankton functional types to inform the design of a global plankton observing system. There might be different designs for different objectives. For example, a key objective might be to measure the planktonic component of the carbon cycle, and we could use biogeochemical models to estimate the global coverage and frequency of observations of the critical zooplankton functional groups. Another key objective might be to measure zooplankton productivity supporting fisheries and we could use ecosystem models that include plankton and fish for this purpose. In this way, we could develop a design – or an amalgamation of a few designs – for a global plankton observing system. Different plankton sampling methods (say time series from nets or zooplankton size spectra from LOPC) can be integrated into a global observing program, although they each measure different yet complementary aspects of the zooplankton community, as do the different oceanographic platforms that currently measure temperature and salinity in GOOS. The key might not be the design itself, but that there is a coherent, defensible vision that the international community could own and promote. Such a design would also provide target against which progress could be measured.

Delivering Indicators for Global Marine Policy

The CPR survey's scale is approaching global coverage and so the survey is uniquely placed to inform transboundary, basin-scale, ocean-scale, and even global-scale management efforts. Besides climate change impacts, which are indeed global, many human induced pressures on the marine environment and biodiversity are transboundary across the EEZs of multiple-countries and from EEZs to the high seas as well, e.g., chemical and debris pollution, fisheries, maritime operations and offshore industries. International policy mechanisms should be established to ensure effective conservation and management planning of global marine ecosystems. The need for such a globally integrated mechanism has been further recognized since the Ocean Summit in 2017 where the UN agreed their commitment to maintain and achieve a "healthy ocean." The spatial extent of the Global Alliance of CPR Surveys enables coherence between different

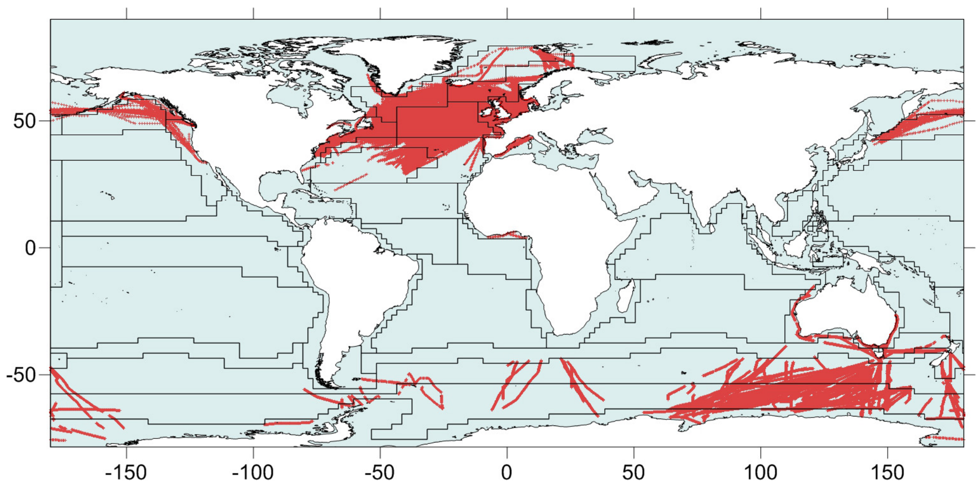

FIGURE 3 | Longhurst Provinces (Flanders Marine Institute, 2009) overlaying CPR sample locations (red). Names of provinces are not shown to avoid clutter but can be found at http://www.marineregions.org/images/boundaries/Longhurst_crop.png.

projects for assessments contributing to international high-level policy and management initiatives.

Several opportunities for contributions of the CPR to global policy mechanisms exist in UN led agendas such as the 2030 Agenda on Sustainable Development Goals (SGDs[3]), Convention of Biological Diversity (CBD) post-2020 global biodiversity framework (Convention on Biological Diversity, 2017), and the conservation and sustainable use of marine biological diversity Beyond Boundaries of National Jurisdiction (BBNJ[4]). For SDG14: Life Below Water, CPR data can provide scientific evidence useful in development of global indicators to report the achievement for the Goal 14.1 on pollution, 14.2 on ecosystem-based approaches, 14.3 on ocean acidification, and 14.5 on marine protected areas. Such indicators could be developed and assessed at the regional or basin scale and reported through national mechanisms, enabling direct comparability between seas and national waters and allowing examination of change in a global context. Plankton information including the CPR data are currently not used in the global indicator suites of the current CBD framework or Aichi Targets despite the fact that the CPR's scientific quality and data coverage could exceed the requirement of these indicators (Chiba et al., 2018). This issue may be solved in the post-2020 framework in which a more harmonized collaboration of different UN organizations, such as IOC-GOOS and UNEP, will be expected.

It is worth noting that both in the SDGs and CBD many of the established or proposed global indicators are to indicate the "response" of society, while the development of robust "state" indicators to indicate the status of the ecosystem and biodiversity, and which are needed to fill the gap of the indicator suites particularly in the marine realm, have not yet been specified. One way to promote this will be by establishing protocols that streamline GOOS EOVs to global indicators. Robust indicators will be developed by coupling plankton EOVs and physical and biogeochemical EOVs (part of the GOOS 2030 strategy, in prep.). This will also strengthen the current Framework for Ocean Observing scheme of global ocean observation (Lindstrom et al., 2012), which has not yet identified the explicit methodology/strategy in feedback of the observation outcome (data) to policy.

Finally, global CPR data can provide scientific evidence useful for negotiating BBNJ where a lack of biodiversity data in the High Seas makes assessment of ecosystems in the High Seas difficult (United Nations, 2017), and has been one of the obstacles for establishment of the internationally agreed (Wright et al., 2016), effective conservation and management policy of BBNJ.

[3] https://www.un.org/sustainabledevelopment/sustainable-development-goals/

[4] https://www.un.org/bbnj/

CONCLUSION

"Locally Strong, Globally Connected" is the rationale that underpins GACS and it remains the best way to develop a global plankton diversity monitoring network. The decade since OceanObs 2009 has seen dramatic changes in the coverage of CPR surveys, collaborative studies and in the degree to which the data are applied to marine resource management policies. As the biological focus of the GOOS matures during the next decade, and with the UN Decade of Ocean Science for Sustainable Development (2021–2030) about to start, the importance of extending GACS and realizing its full potential could not be greater, nor more timely. A global network of CPR surveys has been initiated. What is needed now is a coordinated approach; to fill gaps in current coverage of large ocean tracts, integrate with other plankton sampling programs that operate in regions not appropriate for CPRs, ground-truth emerging technologies and satellite observations, and integrate with other Essential Ocean Variables to build an efficient global observing program for the open ocean.

AUTHOR CONTRIBUTIONS

SB contributed to significant pieces of text throughout the study. AM-G and SC contributed to the policy sections. ME contributed to the ESR section. RA-A contributed to **Table 1**. AR contributed to the sections "Review of the Different Funding Models" and "Becoming Truly Global." GG, RJ, JK, PK, EM, CO, KR, KT, HV, and WW contributed to shorter contributions sections throughout the study.

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REFERENCES

Batten, S. D., Allen, R. J. S., and Wotton, C. O. M. (1998). The effects of the Sea Empress oil spill on the plankton of the Southern Irish Sea. *Mar. Pollut. Bull. Pergamon* 36, 764–774. doi: 10.1016/S0025-326X(98)00039-3

Batten, S. D., and Burkill, P. H. (2010). The continuous plankton recorder: towards a global perspective. *J. Plankt. Res.* 2010, 1619–1621. doi: 10.1093/plankt/fbq140

Batten, S. D., Clarke, R. A., Flinkman, J., Hays, G. C., John, E. H., John, A. W. G., et al. (2003a). CPR sampling – The technical background, materials and methods, consistency and comparability. *Prog. Oceanogr.* 58, 193–215. doi: 10.1016/j.pocean.2003.08.004

Batten, S. D., Walne, A. W., Edwards, M., and Groom, S. B. (2003b). Phytoplankton biomass from continuous plankton recorder data: an assessment of the phytoplankton colour index. *J. Plankt. Res.* 25, 697–702. doi: 10.1093/plankt/25.7.697

Batten, S. D., Ruggerone, G. T., and Ortiz, I. (2018). Pink Salmon induce a trophic cascade in plankton populations in the southern Bering Sea and around the Aleutian Islands. *Fish. Oceanogr.* 27, 548–559. doi: 10.1111/fog.12276

Beaugrand, G., Brander, K. M., Lindley, J. A., Souissi, S., and Reid, P. C. (2003). Plankton effect on cod recruitment in the North Sea. *Nature* 426, 661–664. doi: 10.1038/nature02164

Beaugrand, G., Reid, P. C., Ibanez, F., Lindley, A. J., and Edwards, M. (2002). Reorganization of North Atlantic marine copepod biodiversity and climate. *Science* 296, 1692–1694. doi: 10.1126/science.1071329

Bedford, J., Johns, D., Greenstreet, S., and McQuatters-Gollop, A. (2018). Plankton as prevailing conditions: a surveillance role for plankton indicators within the marine strategy framework Directive. *Mar. Policy* 89, 109–115. doi: 10.1016/j.marpol.2017.12.021

Boalch, G. T., and Harbour, D. S. (1977). Unusual diatom off the coast of south-west England and its effect on fishing. *Nature* 269, 687–688. doi: 10.1038/269687a0

Boss, E., Waite, A., Muller-Karger, F., Yamazaki, H., Wanninkhof, R., Uitz, J., et al. (2018). Beyond chlorophyll fluorescence: the time is right to expand biological measurements in ocean observing programs. *Limnol. Oceanogr. Bull.* 27, 89–90. doi: 10.1002/lob.10243

Brewin, R. J. W., Sathyendranath, S., Hirata, T., Lavender, S. J., Barciela, R., and Hardman-Mountford, N. J. (2010). A three-component model of phytoplankton size class for the Atlantic Ocean. *Ecol. Model.* 221, 1472–1483. doi: 10.1016/j.ecolmodel.2010.02.014

Chandler, P. C., King, S. A., and Boldt, J. (eds) (2017). State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2016. *Can Tech. Rep. Fish. Aquat. Sci.* 3225:243.

Chiba, S., Batten, S., Martin, C. S., Ivory, S., Miloslavich, P., and Weatherdon, L. V. (2018). Zooplankton monitoring to contribute towards addressing global biodiversity conservation challenges. *J. Plankt. Res.* 40, 509–518. doi: 10.1093/plankt/fby030

Clark, R. A., Frid, C. L. J., and Batten, S. (2001). A critical comparison of two long-term zooplankton time series from the central-west North Sea. *J. Plank. Res.* 23, 27–39. doi: 10.1093/plankt/23.1.27

Convention on Biological Diversity (2017). *Recommendation Adopted by the Subsidiary Body on Science, Technical and Technological Advice*. Available at: https://www.cbd.int/doc/recommendations/sbstta-21/sbstta-21-rec-01-en.pdf (accessed October, 2018).

Di Cesare, A., Petrin, S., Fontaneto, D., Losasso, C., Eckert, E. M., Tassistro, G., et al. (2018). ddPCR applied on archived continuous plankton recorder samples reveals long-term occurrence of class 1 integrons and a sulphonamide resistance gene in marine plankton communities. *Environ. Microbiol. Rep.* 10, 458–464. doi: 10.1111/1758-2229.12665

Duarte, C. M., Conley, D. J., Carstensen, J., and Sánchez-Camacho, M. (2009). Return to neverland: shifting baselines affect eutrophication restoration targets. *Estuar. Coasts* 32, 29–36. doi: 10.1007/s12237-008-9111-2

Edwards, M., Beaugrand, G., Hays, G. C., Koslow, J. A., and Richardson, A. J. (2010). Multi-decadal oceanic ecological datasets and their application in marine policy and management. *Trends Ecol. Evol.* 25, 602–610. doi: 10.1016/j.tree.2010.07.007

Edwards, M., Helaouet, P., Alhaija, R. A., Batten, S., Beaugrand, G., Chiba, S., et al. (2016). *Global Marine Ecological Status Report: Results from the Global CPR Survey 2014/2015*. SAHFOS Technical Report, 11, 1–32. Plymouth.

Edwards, M., John, A. W. G., Johns, D. G., and Reid, P. C. (2001). Case history and persistence of the non-indigenous diatom *Coscinodiscus wailesii* in the north-east Atlantic. *J. Mar. Biol. Assoc.* 81, 207–211. doi: 10.1017/S0025315401003654

Edwards, M., Johns, D. G., Richardson, A. J., Leterme, S. C., Svendsen, E., and Richardson, A. J. (2006). Regional climate change and harmful algal blooms in the northeast Atlantic. *Limnol. Oceanogr.* 51, 820–829. doi: 10.4319/lo.2006.51.2.0820

Evans, K., Bax, N. J., and Smith, D. C. (2016). Australia state of the environment. *Mar. Environ.* 226, 134–146. doi: 10.1093/biosci/biw180

Flanders Marine Institute (2009). *Longhurst Provinces*. Ostend: Flanders Marine Institute.

Hallegraeff, G., Coman, F., Davies, C., Hayashi, A., Mcleod, D., Slotwinski, A., et al. (2014). Australian dust storm associated with extensive *Aspergillus sydowii* Fungal "Bloom" in Coastal Waters. *Appl. Environ. Microbiol.* 80, 3315–3320. doi: 10.1128/AEM.04118-13

Hill, K., Moltmann, T., Proctor, R., and Allen, S. (2010). The Australian integrated marine observing system: delivering data streams to address national and international research priorities. *Mar. Tech. Soc. J.* 44, 65–72. doi: 10.403/MTSJ.44.6.13

Hinder, S. L., Gravenor, M. B., Edwards, M., Ostle, C., Bodger, O. G., Lee, P. L. M., et al. (2014). Multi-decadal range changes vs. thermal adaptation for north east Atlantic oceanic copepods in the face of climate change. *Glob. Change Biol.* 20, 140–146. doi: 10.1111/gcb.12387

Hosie, G., Mormede, S., Kitchener, J., Takahashi, K., and Raymond, B. (2014). "Near surface zooplankton communities," in *The CAML/SCAR-MarBIN Biogeographic Atlas of the Southern Ocean*, eds C. De Broyer, P. Koubbi, H. Griffiths, et al. (Cambridge: Scientific Committee on Antarctic Research).

Innes, L., Simcock, A., Ajawin, A. Y., Alcala, A. C., Bernal, P., Calumpong, H. P., et al. (2016). *The First Global Integrated Marine Assessment: World Ocean Assessment 1*. New York, NY: United Nations.

John, E. H., Batten, S. D., Harris, R. P., and Hays, G. C. (2001). Comparison between zooplankton data collected by the Continuous Plankton Recorder survey in the English Channel and by WP-2 nets at station L4, Plymouth (UK). *J. Sea Res.* 46, 223–232. doi: 10.1016/S1385-1101(01)00085-5

Kavanaugh, M. T., Oliver, M. J., Chavez, F. P., Letelier, R. M., Muller-Karger, F. E., and Doney, S. C. (2016). Seascapes as a new vernacular for pelagic ocean monitoring, management and conservation. *ICES J. Mar. Sci.* 73, 1839–1850. doi: 10.1093/icesjms/fsw086

Koslow, J. A. (1983). Zooplankton community structure in the north sea and northeast atlantic: development and test of a biological model. *Can. J. Fish. Aquat. Sci.* 40, 1912–1924. doi: 10.1139/f83-222

Koslow, J. A., and Couture, J. (2013). Ocean sciences: follow the fish. *Nature* 502, 163–164. doi: 10.1038/502163a

Lewis, K., Allen, J. I., Richardson, A. J., and Holt, J. T. (2006). Error quantification of a high resolution coupled hydrodynamic-ecosystem coastal-ocean model: part 3, validation with continuous plankton recorder data. *J. Mar. Syst.* 63, 209–224. doi: 10.1016/j.jmarsys.2006.08.001

Lindstrom, E., Gunn, J., Fischer, A., McCurdy, A., and Glover, L. K. (2012). *A Framework for Ocean Observing. By the Task Team for an Integrated Framework for Sustained Ocean Observing*. Paris: UNESCO.

Longhurst, A. R. (1998). *Ecological Geography of the Sea*. San Diego: Academic Press, 397.

Longhurst, A. R. (2007). *Ecological geography of the sea*. London: Academic Press.

McQuatters-Gollop, A., Edwards, M., Helaouët, P., Johns, D. G., Owens, N. J. P., Raitsos, D. E., et al. (2015). The continuous plankton recorder survey: how can long-term phytoplankton datasets deliver good environmental status? *Estuar. Coast. Shelf Sci.* 162, 88–97. doi: 10.1016/j.ecss.2015.05.010

McQuatters-Gollop, A., Johns, D. G., Bresnan, E., Skinner, J., Rombouts, I., Stern, R. F., et al. (2017). From microscope to management: the critical value of plankton taxonomy to marine policy and biodiversity conservation. *Mar. Policy* 83, 1–10. doi: 10.1016/j.marpol.2017.05.022

McQuatters-Gollop, A., Raitsos, D. E., Edwards, M., Pradhan, Y., Mee, L. D., Lavender, S. J., et al. (2007). A long-term chlorophyll dataset reveals regime shift in North Sea phytoplankton biomass unconnected to nutrient levels. *Limnol. Oceanogr.* 52, 635–648. doi: 10.4319/lo.2007.52.2.0635

Miesner, A. K., and Payne, M. R. (2018). Oceanographic variability shapes the spawning distribution of blue whiting (Micromesistius poutassou). *Fish. Oceanogr.* 27, 623–638. doi: 10.1111/fog.12382

Miloslavich, P., Bax, N. J., Simmons, S. E., Klein, E., Appeltans, W., Aburto-Oropeza, O., et al. (2018). Essential ocean variables for global sustained observations of biodiversity and ecosystem changes. *Glob. Change Biol.* 2018, 2416–2433. doi: 10.1111/gcb.14108

Moltmann, T. (2011). "Ocean observing systems a national perspective from Australia," in *Proceedings of the GEOSS Workshop XLII - Oceans*, (Kona, HI: *IEEE*), doi: 10.1109/GEOSS-XLII.2011.6105429

National Research Council (1997). *The Global Ocean Observing System: Users, Benefits, and Priorities*. Washington, DC: The National Academies Press, doi: 10.17226/5580

Ohman, M. D., Davis, R. E., Sherman, J. T., Grindley, K. R., Whitmore, B. M., Nickels, C. F., et al. (2019). Zooglider: An autonomous vehicle for optical and acoustic sensing of zooplankton. *Limnol. Oceanogr. Methods* 17, 69–86. doi: 10.1002/lom3.10301

OSPAR (2017). *Intermediate Assessment 2017*. Available at: https://oap.ospar.org/en/ospar-assessments/intermediate-assessment-2017 (accessed October, 2018).

Planque, B., and Fromentin, J. M. (1996). Calanus and environment in the eastern North Atlantic.1. Spatial and temporal patterns of *C-finmarchicus* and *C-helgolandicus*. *Mar. Ecol. Prog. Ser.* 134, 101–109. doi: 10.3354/meps134101

Pörtner, H.-O., Karl, D. M., Boyd, P. W., Cheung, W. W. L., Lluch-Cota, S. E., Nojiri, Y., et al. (eds) (2014). "Ocean systems," in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds C. B. Field, V. R. Barros, D. J. Dokken, et al. (Cambridge: Cambridge University Press), 411–484.

Raitsos, D. E., Walne, A., Lavender, S. J., Licandro, P., Reid, P. C., and Edwards, M. (2013). A 60-year ocean colour data set from the continuous plankton recorder. *J. Plankt. Res.* 35, 158–164. doi: 10.1093/plankt/fbs079

Reid, P. C., Battle, E. J. V., Batten, S. D., and Brander, K. M. (2000). Impacts of fisheries on plankton community structure. *ICES J. Mar. Sci.* 57, 495–502. doi: 10.1006/jmsc.2000.0740

Rêve-Lamarche, A.-H., Séverine, A., Racault, M.-F., Dessailly, D., Guiselin, N., Jamet, C., et al. (2017). Estimation of the potential detection of diatom assemblages based on ocean color radiance anomalies in the North Sea. *Front. Mar. Sci.* 4:408. doi: 10.3389/fmars.2017.00408

Richardson, A. J., Eriksen, R. S., and Rochester, W. (2015). *Plankton 2015: State of Australia's oceans. CSIRO Report*. Canberra: CSIRO.

Richardson, A. J., John, E. H., Irigoien, X., Harris, R. P., and Hays, G. C. (2004). How well does the Continuous Plankton Recorder (CPR) sample zooplankton? A comparison with the Longhurst Hardy Plankton Recorder (LHPR) in the northeast Atlantic. *Deep Sea Res. Part 1 Oceanogr. Res. Pap.* 51, 1283–1294. doi: 10.1016/j.dsr.2004.04.002

Richardson, A. J., Walne, A. W., John, A. W. G., Jonas, T. D., Lindley, J. A., Sims, D. W., et al. (2006). Using continuous plankton recorder data. *Prog. Oceanogr.* 68, 27–74. doi: 10.1016/j.pocean.2005.09.011

Richardson, A. J., and Schoeman, D. S. (2004). Climate impact on plankton ecosystems in the northeast Atlantic. *Science* 305, 1609–1612. doi: 10.1126/science.1100958

Robinson, K. V., Pinkerton, M. H., Hall, J. A., and Hosie, G. W. (2014). *Continuous Plankton Recorder Time Series. New Zealand Aquatic Environment and Biodiversity Report No.* 128. Wellington: Ministry for Primary Industries.

Schartup, A. T., Qureshi, A., Dassuncao, C., Thackray, C. P., Harding, G., and Sunderland, E. M. (2018). A model for Methylmercury uptake and trophic transfer by marine plankton. *Environ. Sci. Technol.* 52, 654–662. doi: 10.1021/acs.est.7b03821

Schminke, H. K. (2007). Entomology for the copepodologist. *J. Plankt. Res.* 29, i149–i162. doi: 10.1093/plankt/fbl073

Sherman, K. (2005). "The large marine ecosystem approach for assessment and management of ocean coastal waters," in *Sustaining Large Marine Ecosystems: the Human Dimension*. eds T. Hennessey and J. Sutinen (Amsterdam: Elsevier), 3–16. doi: 10.1016/s1570-0461(05)80025-4

Skerratt, J. H., Mongin, M., Wild-Allen, K. A., Baird, M. E., Robson, B. J., Schaffelke, B., et al. (2019). Plankton and nutrient dynamics on the Great Barrier Reef: Skill assessment and analysis of the eReefs biogeochemical model. *J. Mar. Syst.* 192, 51–74.

Spalding, M. D., Fox, H. E., Allen, G. R., Davidson, N., Ferdaña, Z. A., Finlayson, M. A. X., et al. (2007). Marine ecoregions of the World: a bioregionalization of coastal and shelf areas. *BioScience* 57, 573–583. doi: 10.1641/b570707

Stern, R. F., Picard, K. T., Hamilton, K. M., Walne, A., Tarran, G. A., Mills, D., et al. (2015). Novel lineage patterns from an automated water sampler to probe marine microbial biodiversity with ships of opportunity. *Prog. Oceanogr.* 137, 409–420. doi: 10.1016/j.pocean.2015.04.015

Thompson, R. C., Olsen, Y., Mitchell, R. P., Davis, A., Steven, J., John, A. W. G., et al. (2004). Lost at sea: where is all the plastic? *Science* 304:838. doi: 10.1126/science.1094559

UNESCO (2017). *What are Marine Ecological Time Series telling us about the ocean? A status report*, eds T. D. O'Brien, L. Lorenzoni, K. Isensee, and L. Valdés (Paris: IOC-UNESCO), 171–190.

United Kingdom Marine Monitoring, and Assessment Strategy [Ukmmas] (2010). *Charting Progress 2: The state of UK seas. An overview*. London: Defra.

United Nations (2017). *The First Global Integrated Marine Assessment*. Cambridge: Cambridge University Press.

Vezzulli, L., Grande, C., Reid, P. C., Hélaouët, P., Edwards, M., Höfle, M. G., et al. (2016). Climate influence on Vibrio and associated human diseases during the past half-century in the coastal North Atlantic. *Proc. Natl. Acad. Sci. U.S.A.* 113, E5062–E5071. doi: 10.1073/pnas.1609157113

Wiebe, P. H., and Benfield, M. C. (2003). From the Hensen net toward four-dimensional biological oceanography. *Prog. Oceanogr.* 56, 7–136. doi: 10.1016/S0079-6611(02)00140-4

Wright, G., Rochette, J., Druel, E., and Gjerde, K. (2016). *The Long and Winding Road Continues: Towards a New Agreement on High Seas Governance*. Paris: *IDDRI*.

Zador, S., and Yasumiishi, E. (2017). *Ecosystem Considerations (2017) Status of the Gulf of Alaska Marine Ecosystem, Stock Assessment and Fishery Evaluation Report*. Anchorage, AK: North Pacific Fishery Management Council.

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Ocean Observing and the Blue Economy

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Sustained ocean observations provide an essential input to ocean scientific research. They also support a wide range of societal and economic benefits related to safety; operational efficiency; and regulation of activities around, on, in, and under seas and the ocean. The ocean economy is large and diverse, accounting for around US$1.5 trillion of global gross value-added economic activity. This is projected to more than double by 2030. Delivering this growth in economic activity is dependent on ocean observations. This review paper summarizes the projected changes in the scale and scope of the ocean economy and the role that observations, measurements, and forecasts play in supporting the safe and effective use of the ocean and ocean resources, at the same time as protecting the environment. It also provides an overview of key future work being planned to develop a better understanding of the present and likely future ocean economy and the role and value of ocean observations in its sustainable realization.

Keywords: ocean observations, ocean information services, ocean observing systems, blue economy, ocean economy, ocean technology

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INTRODUCTION

The ocean is a key source of food, energy, and minerals. It is the primary medium upon which global trade takes place. Approximately 40% of the world's population live in coastal regions and three quarters of the world's large cities are located on the coast. Coastal waters and regions are the location of a large proportion of global tourism and recreational activity.

Ecosystem services provided by the ocean play a pivotal role in human society. Hundreds of millions of people depend directly on the ocean for their food and livelihoods. We all depend on the ocean for provision of much of the oxygen that we breathe and for its controlling and moderating role in weather and climate.

In its report on the ocean economy, the Organisation for Economic Co-operation and Development (OECD, 2016) estimates that 2010 economic activities associated with the ocean amounted to around US$1.5 trillion. The OECD projects rapid growth in economic activity associated with the ocean, with ocean-based industries having the potential to outperform the growth of the global economy, both in terms of value added and employment. Their projections suggest that between 2010 and 2030 the ocean economy could more than double its contribution to global value added, reaching over US$3 trillion per annum.

The marine and maritime industries delivering this economic activity continue to undergo a profound transition. As well as the traditional industries of shipping, capture fisheries, tourism, and marine recreation; there is now large-scale industrial activity associated with exploitation of offshore oil and gas, the harnessing of marine renewable energy, and aquaculture-based food production, as well as emerging new activities, such as ocean mining and marine biotechnology (**Table 1**).

In contrast to the terrestrial environment, the ocean represents a difficult and harsh environment in which to operate. Much of the economic activity around, on, in, and under the ocean would not be possible without data, information, and knowledge derived from sustained ocean observations, measurements, and forecasts, which underpin safe and cost-effective marine and maritime activity.

The ocean environment is subject to a complex range of pressures. Foremost are those related to ocean health: over-exploitation of marine resources, pollution, rising ocean temperatures and levels, ocean acidification, and loss of biodiversity. Unsustainable use of the ocean and its resources threatens the basis on which much of the world's welfare and prosperity depends. Here too ocean observations, measurements, and forecasts play a fundamental role in underpinning the scientific basis for national and international legislation to regulate the use of the ocean and protect the ocean environment. Sustained observations also provide the basis for monitoring of regulatory compliance and effectiveness as well as playing a key role in supporting the valuation of natural assets and ecosystem services. It is only through understanding this wider blue economy, which encompasses both the economic uses of the ocean and ocean resources, and the natural assets and ecosystem services that the ocean provides, that a truly sustainable ocean economy can be delivered.

As ocean scientific research and operational ocean information needs have grown in scale, the provision of the means to conduct ocean observations and measurements has become an important economic activity in its own right. The growth of the ocean economy is also driving the development of an important service sector comprising value-added intermediaries, who add value to public and private ocean observations, measurements, and forecasts, tailoring them for specific end-uses.

TABLE 1 | Established and emerging ocean-based industries (adapted from OECD, 2016).

Established	Emerging
Capture fisheries and aquaculture	Open water aquaculture
Seafood processing	Deep- and ultra-deep-water oil and gas
Shipping	Offshore wind energy
Ports	Ocean renewable energy
Shipbuilding and repair	Marine and seabed mining
Offshore oil and gas (shallow water)	Maritime safety and surveillance
Marine manufacturing and construction	Marine biotechnology
Maritime and coastal tourism	High-tech marine products and services
Marine business services	Others
Marine R&D and education	

This review paper summarizes work on the scale, scope, and likely future trajectory of the ocean economy; the role that ocean observations have in underpinning this growing economic activity while ensuring protection of the marine environment; and the role of technology producers and intermediary service providers in enabling ocean observation capabilities and the delivery of operational benefits to those that use the ocean and ocean resources.

THE OCEAN ECONOMY

The following overview is derived from the OECD *Ocean Economy 2030* report (OECD, 2016). This report describes the global ocean economy and its likely future growth trajectory building on an extensive body of published work. The comprehensive bibliography contained in the OECD report provides a valuable resource for those seeking a better understanding of the body of work supporting production of this report.

The OECD report describes the ocean as the new economic frontier, holding the promise of immense resource wealth and with great potential for boosting economic growth, employment, and innovation. It recognizes the role of the ocean in many of the global challenges facing the planet in the decades to come from world food security and climate change to the provision of energy, natural resources, and improved medical care. While the potential of the ocean to help meet these challenges is huge, the report also recognizes that the ocean is already under stress from over-exploitation, pollution, declining biodiversity, and climate change. Realizing the potential of the ocean will therefore demand responsible, sustainable approaches to its economic development.

The blue economy encompasses ocean-based industries (for example, shipping, fishing, offshore wind, and marine biotechnology) and the natural assets and ecosystem services that the ocean provides (for example, fish, shipping lanes, and CO_2 absorption). As these two aspects are inextricably inter-linked, the OECD report addresses many aspects of ecosystem services and ecosystem-based management as well as focusing on the ocean-industry dimension.

The global ocean economy, measured in terms of the ocean-based industries' contribution to economic output and employment, is significant. Preliminary calculations based on the OECD's Ocean Economy Database value the ocean economy's contribution in 2010 very conservatively at US$1.5 trillion, or approximately 2.5% of world gross value added. Offshore oil and gas accounted for one-third of total value added of the ocean-based industries, followed by maritime and coastal tourism, maritime equipment, and ports. Direct full-time employment in the ocean economy amounted to around 31 million jobs in 2010. The largest employers were industrial capture fisheries with over one-third of the total, and maritime and coastal tourism with almost one-quarter.

Economic activity in the ocean is expanding rapidly, driven primarily by developments in global population, economic growth, trade, rising income levels, and the impact of technological advances. An important constraint on the development of the ocean economy is the current deterioration of ocean health. As anthropogenic carbon emissions have risen over time, the ocean has absorbed much of the carbon, leading to ocean acidification. Sea temperatures and sea levels are rising and ocean currents shifting, resulting in biodiversity and habitat loss, changes in fish stock composition and migration patterns, and higher frequency of severe ocean weather events. The prospects for future ocean development are further aggravated by land-based pollution, in particular agricultural run-off, chemicals, and macro- and micro-plastic pollutants that feed into the ocean from rivers, as well as by overfishing and depleted fish stocks in many parts of the world.

Looking ahead to 2030, many ocean-based industries have the potential to outperform the growth of the global economy as a whole, both in terms of value added and employment. The OECD projections suggest that between 2010 and 2030, on a business-as-usual scenario basis, the ocean economy could more than double its contribution to global value added, reaching over US$3 trillion. Particularly strong growth is expected in marine aquaculture, offshore wind, fish processing, and shipbuilding and repair. Ocean industries also have the potential to make an important contribution to employment growth. In 2030, they are anticipated to employ approximately 40 million full-time equivalent jobs under a business-as-usual scenario. The fastest growth in jobs is expected to occur in offshore wind energy, marine aquaculture, fish processing, and port activities (**Table 2**).

A number of countries are engaged in the production of satellite accounts seeking to describe and quantify ocean economy-related activity at a national level. Meetings have been held to seek to harmonize the basis for these studies. These include the Center for the Blue Economy *ocean summit on reaching consensus on national ocean accounts* hosted by the Middlebury Institute of International Studies in 2015, a follow up meeting sponsored by the Chinese National Marine Data Information Center in 2016, and the *new approaches to evaluating the ocean economy symposium* held at the OECD in November 2017, with lessons learned and outcomes summarized in the OECD report *Rethinking Innovation for a Sustainable Ocean Economy* (OECD, 2019).

OCEAN OBSERVING IN SUPPORT OF A SUSTAINABLE OCEAN ECONOMY

The ultimate beneficiaries of ocean observations are end-users whose activities or businesses benefit from ocean data and information in terms of better scientific understanding of the ocean, improved safety, economic efficiency gains or more effective regulation of ocean use, and the protection of the ocean environment.

End-users of ocean data and information fall into four main types:

- *Science end-users* who undertake research activities that rely in whole or in part on sustained measurement and observation of the ocean.
- *Operational end-users* who make use of ocean data and information to support operational needs related to safety, economic efficiency, and protection of the environment.
- *Policy end-users* who require sustained ocean data and information to support policy formulation, monitoring of policy compliance, and assessment of policy effectiveness.
- *Public end-users* who have a general interest in the ocean or make use of ocean data and information in support of their leisure activities or recreational pursuits.

The role of the scientific community is twofold when it comes to ocean observations. Science is not only a user but also the major producer of ocean observations. Scientific interest initiates ocean observation. It also motivates the development of suitable and efficient measurement instruments, from individual sensors to complex observing systems. Science end-users make use of sustained ocean observations to underpin the data and information needs of many different research areas. Examples are the use of ocean data and information in support of research into

TABLE 2 | Overview of estimates of industry-specific growth rates in value added and employment 2010 and 2030 (OECD, 2016).

Industry	Compound annual growth rate for GVA between 2010 and 2030	Total change in GVA between 2010 and 2030	Total change in employment between 2010 and 2030
Industrial marine aquaculture	5.69%	303%	152%
Industrial capture fisheries	4.10%	223%	94%
Fish processing	6.26%	337%	206%
Maritime and coastal tourism	3.51%	199%	122%
Offshore oil and gas	1.17%	126%	126%
Offshore wind	24.52%	8 037%	1 257%
Port activities	4.58%	245%	245%
Shipbuilding and repair	2.93%	178%	124%
Maritime equipment	2.93%	178%	124%
Shipping	1.80%	143%	130%
Average of the total ocean-based industries	3.45%	197	130
Global economy between 2010 and 2030	3.64%	204	120

understanding physical, chemical, and biological processes in the ocean or the scientific study of the role of the oceans in weather and climate.

As users of ocean observations, scientists develop methods to edit and analyze the data and derive insights on the ocean and its dynamics. These insights contribute to society's knowledge pool and are used to develop, for example, forecasts, assessments, and recommendations for decision makers. Science also lays the groundwork for policy and operational use of ocean observations.

Operational end-users make use of ocean data and information to support strategic decision making and operational planning. For example, an offshore oil and gas company might use information products derived in part from ocean data and information to support the optimum and safe design of a facility or to help plan safe drilling activities.

Policy end-users depend on ocean data and information to help inform the drafting of effective legislation to ensure safety of life or property, protection of the environment, or regulation of the use of ocean space and ocean resources. Ocean data and information are further needed to monitor compliance with the resulting legislation (for example, monitoring to determine beach closures under the US Environmental Protection Agency Clean Water Act). Ocean data and information also deliver benefits in terms of measuring policy effectiveness, for example, determining the effectiveness of a policy to reduce concentrations of a harmful pollutant requires long-term monitoring to determine whether the policy is delivering on this goal.

The public at large is an important stakeholder in the ocean economy and end-user of ocean data and information. Surfing, sailing, diving, sport fishing, and coastal tourism are all significant ocean economic activities. Those engaged in these recreational and leisure activities increasingly make use of open access and commercial ocean data and information products.

Supporting all of these end-uses are the means to make ocean observations and measurements and the capacity to turn the resulting data into useful actionable information. These activities are in of themselves an important component of the overall ocean economy comprising:

- *Providers* of observing system infrastructure;
- *Producers* of ocean observations;
- *Intermediate users* who tailor ocean data or information for a specific end-use.

Providers of observing system infrastructure include manufacturers of sensors, instruments, and platforms; those building, launching, and operating satellite systems; providers of the cyber infrastructure that interconnects observing system components; and organizations that develop and maintain the data management systems, software tools, and models that are used to help turn data into useful information.

Producers of ocean observations are primarily public organizations. Ocean observation is conducted by a variety of national, regional, and international institutions and initiatives on different spatial scales. Many countries have installed marine research infrastructure and ocean observatories. Regions have combined their efforts to observe different parts of the ocean collectively and to share and combine collected data.

Under the aegis of the Global Ocean and Observing System (GOOS) and the Global Earth Observation System of Systems (GEOSS), efforts in establishing national ocean observing systems have been progressively increasing. Almost every coastal country is involved in marine research and activities related to ocean observation. Examples of mature ocean observing systems are the Australian Integrated Marine Observing System, the Canadian Ocean Networks, the Japan Oceanographic Data Center, the European Global Ocean Observing System (EuroGOOS), and the associated Copernicus Marine Environmental Monitoring Service (CMEMS) as well as the US Integrated Ocean Observing System (IOOS). Additionally, the Canadian IOOS was established in March 2019 to further develop and integrate ocean research and observing networks into a national system to support the coastal economy and build resilient coastal infrastructure.

In addition to this public sector activity, many business end-users of ocean observations commission their own sustained data collection to support operational needs where these cannot be met through the use of publicly available operational ocean data and information. In these instances, end-users generally place contracts with specialist ocean measurement businesses who undertake such work on their behalf. In some cases, public organizations also contract to private companies in similar ways.

Intermediate users are public and private organizations that add value to ocean data and information tailoring it for specific end-uses. In this context it is important to recognize that delivery of end-user benefit is often not a simple linear end to end service chain. More usually, benefits are delivered by multiple organizations merging and mashing different sources of data and information to derive a product useful for a particular purpose. Growth in the ocean economy is driving the development of a significant service industry meeting the specialist information needs of different sectors.

UNDERSTANDING THE CONTRIBUTION OF OCEAN OBSERVATION TO QUANTIFYING THE BLUE ECONOMY

The economic and societal benefits underpinned by ocean observations, measurements, and forecasts are large. However, they are difficult to quantify. There have been no comprehensive global attempts to describe and quantify these benefits, although numerous case studies have sought to understand and quantify socioeconomic benefits associated with the use of ocean data in support of specific ocean uses or regulatory measures. In aggregate, the cost of obtaining and using ocean observations is almost certainly only a small percentage of the value of the benefits derived.

Recent work by the OECD has sought to collate and summarize the existing literature concerning the benefits of sustained ocean observations (OECD, 2019).

Science remains a crucial driver for most ocean observations. Observations and measurements derived from diverse platforms (e.g., *in situ*, research vessels, satellite remote sensing) contribute to advancing fundamental knowledge on the ocean, weather, and the climate, directly and via their use in driving, calibrating, and verifying ocean, atmospheric, and climate models. In the Intergovernmental Oceanographic Commission's (IOC) Global Ocean Science Report (IOC, 2017), around 80% of data centers that provide ocean observation data, products, and services named scientific communities as their most important end-users.

Many of the societal benefits associated with improved science are not readily associated with economic value, partly because they do not flow through markets and do not generate economic benefits in and of themselves. For this reason, the literature has often considered ocean observations data to be a public good, the benefits of which are difficult to identify and value. Despite the relative complexity of valuing societal benefits, a number of recent studies have used a range of methodologies to do so. Further valuation of societal benefits is of particular importance to undertaking a thorough assessment of the value of ocean observing systems and is of crucial importance to any future overall economic assessment.

There are a wide diversity of operational products and services based on sustained ocean observations. Based on the OECD literature review, weather forecasts (36%), sea state forecasts (21%), and climate forecasts (7%) are the products and services most taken up for operational use. Some of the traditional operational user groups include navies and coastguards, offshore oil and gas industry, commercial shipping fisheries, and aquaculture. User domains benefiting from ocean observations and covered the most by the literature do not paradoxically mirror the distribution of these traditional user groups. This is because much of the work on quantifying these areas exists only in the "gray" literature rather than as peer-reviewed material. The socioeconomic assessments consider primarily aquaculture and fisheries (13%), agriculture (9%), environmental management (8%), tourism and cruises (8%), pollution and oil spills (8%), military, search and rescue (8%), and commercial shipping and maritime transport (8%).

While ongoing efforts are to be commended and recent progress has been made on mapping operational user communities, data on intermediate and end users are often not collected. To date, only one systematic study of national commercial intermediary activity has been completed in the form of the National Oceanic and Atmospheric Administration (NOAA) Ocean Enterprise Study (Rayner et al., 2018) which sought to quantify the scope, scale, and value of commercial provider and intermediate user activity by US companies.

NEXT STEPS

A thorough assessment of the value of ocean observations requires further effort in identifying and understanding the different communities of intermediate and end-users, their use of ocean observations and the associated benefits, based on common standards for the evaluation process. Quantifying socio-economic benefits of ocean observing activity in support of the ocean economy will support a stronger argument for the sustainability and improvement of ocean observations.

The following steps could contribute to achieving this:

Increased efforts among providers of ocean observations to track user groups, their downloads, and use of the data would help identify associated marketable and societal values. This would involve improved identification and mapping of end-users, both scientific or operational. Dedicated surveys of end-users of ocean observations could be a useful tool to further characterize users, the products and services they require, and the benefits they realize by using ocean observations. These surveys could be conducted in co-operation with open data platforms, such as the Australian Open Data Network, CMEMS, EMODnet, or US IOOS, with their user bases as the target survey groups. CMEMS already gathers some of this information through its user registration process.

A more thorough and detailed analysis of dedicated value chains for some of the main products and services derived from ocean observations could also contribute to a more robust valuation of socioeconomic benefits. There are useful efforts underway at international and national levels (e.g., work by IOC, NOAA, and under the European AtlantOS project, as well as a recently commenced project being undertaken by US IOOS Regional Associations) to survey their users. Convening an expert meeting specifically on lessons learnt from mapping user groups and value chains would be very useful for the ocean observing community.

Studies differ considerably in spatial and temporal scope, methodology used, and user domain considered. The ocean observation community would benefit from international standards or guidelines for the valuation of ocean observations. This would simplify the comparison of different studies and allow the aggregation of results. There are several general challenges when assessing the benefits of ocean observations, e.g., the public good character of many ocean observations, complex value chains, and taking stock of a variety of stakeholders. Comparing the results of individual studies can be complicated by varying temporal, sectoral, and spatial scales applied in the assessments. Improvements in methodologies are, however, possible. The weather and the environmental policy communities have both tested and paved the way for useful and proven value of information techniques that may be applicable to ocean observations.

In conclusion, recent years have seen a rapidly growing awareness of the importance of our seas and ocean as a key natural resource and engine of economic growth. Harnessing and simultaneously safeguarding the ocean economy require deeper knowledge and much more data than are currently available. The OECD has an ambitious workplan for the 2019–2020 period aimed at better understanding key aspects of the ocean economy and the use of ocean observations. Following on from OECD's current study on the socioeconomic valuation of sustained ocean observations, this work will include targeted questionnaire-based surveys aimed at gaining a better understanding of who uses data from sustained ocean observations and measurements.

AUTHOR CONTRIBUTIONS

RR: preparation of section "Ocean Observing in Support of a Sustainable Ocean Economy" and compilation of overall review. CJ: contributions from OECD. CG: contributions to section "Understanding the Contribution of Ocean Observation to Quantifying the Blue Economy."

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REFERENCES

IOC (2017). *Global Ocean Science Report: The Current Status of Ocean Science Around the World. Intergovernmental Oceanographic Commission*. Paris: UNESCO Publishing.

OECD (2016). *The Ocean Economy in 2030*. Paris: OECD Publishing.

OECD (2019). *Rethinking Innovation for a Sustainable Ocean Economy*. Paris: OECD Publishing.

Rayner, R., Gouldman, C., and Willis, Z. (2018). The Ocean Enterprise – understanding and quantifying business activity in support of observing, measuring and forecasting the ocean. *J. Operat. Oceanogr.* doi: 10.1080/1755876X.2018.1543982

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Atlantic Meridional Overturning Circulation: Observed Transport and Variability

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The Atlantic Meridional Overturning Circulation (AMOC) extends from the Southern Ocean to the northern North Atlantic, transporting heat northwards throughout the South and North Atlantic, and sinking carbon and nutrients into the deep ocean. Climate models indicate that changes to the AMOC both herald and drive climate shifts. Intensive trans-basin AMOC observational systems have been put in place to continuously monitor meridional volume transport variability, and in some cases, heat, freshwater and carbon transport. These observational programs have been used to diagnose the magnitude and origins of transport variability, and to investigate impacts of variability on essential climate variables such as sea surface temperature, ocean heat content and coastal sea level. AMOC observing approaches vary between the different systems, ranging from trans-basin arrays (OSNAP, RAPID 26°N, 11°S, SAMBA 34.5°S) to arrays concentrating on western boundaries (e.g., RAPID WAVE, MOVE 16°N). In this paper, we outline the different approaches (aims, strengths and limitations) and summarize the key results to date. We also discuss alternate approaches for capturing AMOC variability including direct estimates (e.g., using sea level, bottom pressure, and hydrography from autonomous profiling floats), indirect estimates applying budgetary approaches, state estimates or ocean reanalyses, and proxies. Based on the existing observations and their results, and the potential of new observational and formal synthesis approaches, we make suggestions as to how to evaluate a comprehensive, future-proof observational network of the AMOC to deepen our understanding of the AMOC and its role in global climate.

Keywords: meridional overturning circulation, thermohaline circulation, observing systems, ocean heat transport, carbon storage, moorings, circulation variability

1. INTRODUCTION

Solar radiation heats the Earth primarily at tropical latitudes, while radiative cooling occurs quasi-uniformly across the globe. To maintain this pattern of heat flux, the atmosphere and ocean redistribute heat from the tropics to the poles with a net poleward heat flux. In the Atlantic, however, the net heat flux is northward, even in the South Atlantic, a distinct feature captured by the Atlantic meridional overturning circulation (AMOC). A measure of the zonally and vertically accumulated flow at each latitude (to be defined below), the AMOC connects northward flowing warm waters and southward flowing cold waters across all latitudes, with the link between northward and southward waters achieved through heat loss to the atmosphere and associated watermass transformation at high latitudes (**Figure 1**). Away from the region of watermass transformation, these southward flowing waters are deep, isolated from atmospheric ventilation, and thus store energy and chemical compounds for hundreds of years. This property of the ocean—storing anomalies at depth—gives the ocean a longer memory than the atmosphere, with the potential to influence climate variability on long timescales.

The influence of AMOC variations occurs on a range of timescales. On seasonal to decadal timescales, fluctuations in the AMOC in the subtropical Atlantic have been suggested to impact coastal sea level off North America (Little et al., 2017) and Atlantic sea surface temperatures (SST, Duchez et al., 2016a), with onward impacts on weather and climate. On multidecadal timescales, the AMOC has been linked to patterns of SST (Atlantic multidecadal variability) with a range of climate implications (e.g., Zhang, 2008). The AMOC also provides a means for removing carbon from the atmosphere and storing it in the deep ocean (Takahashi and Coauthors, 2009; Perez et al., 2013). For in-depth reviews of the AMOC, its variability and consequences see Lozier (2012) and Buckley and Marshall (2016).

Due to the importance of AMOC variability in the climate system, the continuously varying strength of the AMOC has been measured at several latitudes, including in the subpolar North Atlantic (since 2014), 26°N (since 2004), 16°N (since 2001) and 34.5°S (since 2009). From the 26°N array, surprisingly large variability was observed on timescales from weeks to a decade (see Srokosz and Bryden, 2015 for a review). However, at two subtropical latitudes (26°N and 16°N) AMOC fluctuations were incoherent: declining at 26°N (Smeed et al., 2014) and intensifying (Frajka-Williams et al., 2018) at 16°N over 2004–2017. Additionally, much of the variability at 26°N on seasonal to interannual timescales is dominated by wind forcing (Zhao and Johns, 2014; Pillar et al., 2016), contradicting the previous hypothesis that buoyancy forcing in subpolar regions drives AMOC variations (Kuhlbrodt et al., 2007). The OSNAP array (spanning latitudes from 53°N to 60°N) was deployed in 2014 to elucidate the relationship between buoyancy forcing and overturning. While multiple efforts toward observing the AMOC have been made in the North Atlantic, the AMOC extends across both hemispheres. An array was deployed at 34.5°S to monitor the mean and time-varying AMOC, as well as the meridional heat and freshwater transport in the South Atlantic. Numerous other data sets (e.g., ship sections, satellite, and Argo profiling float observations) have been used to characterize AMOC variability and structure over the past two decades.

In this paper, we give an overview of the present state of AMOC observations, starting with a definition of the AMOC strength (section 1.1) and history of AMOC observing (section 1.2), followed by an overview of the present-day continuous observing systems using full-height boundary mooring arrays (section 2). Section 3 discusses alternate approaches to direct measurements of the AMOC, using sea level and bottom pressure gradients, supplemented in some cases by hydrographic data. Section 4 describes inverse approaches to AMOC estimation. These three sections provide an overview of the existing state of AMOC observations. Section 5 gives a forward-looking approach to observing the AMOC, while section 6 notes gaps in the current observing approaches. Section 7 concludes.

1.1. AMOC Definition

The AMOC is commonly defined at a given latitude using a streamfunction Ψ in units of Sverdrups (1 Sv = 10^6 m^3/s)—the zonally-integrated and vertically-accumulated meridional volume transport in depth coordinates. Absolute meridional velocities v are required across the full-depth section. For the AMOC strength determined in depth coordinates (MOC_z), velocities are integrated with depth and along the section from west (x_w) to east (x_e) where the transport streamfunction is

$$\Psi(z) = \int_z^0 \int_{x_w}^{x_e} v(x, z')\, dx\, dz' \,. \quad (1)$$

While the definition is typically applied at a fixed latitude, it can be adapted for any coast-to-coast section using x as an along-section coordinate with horizontal velocities v perpendicular to

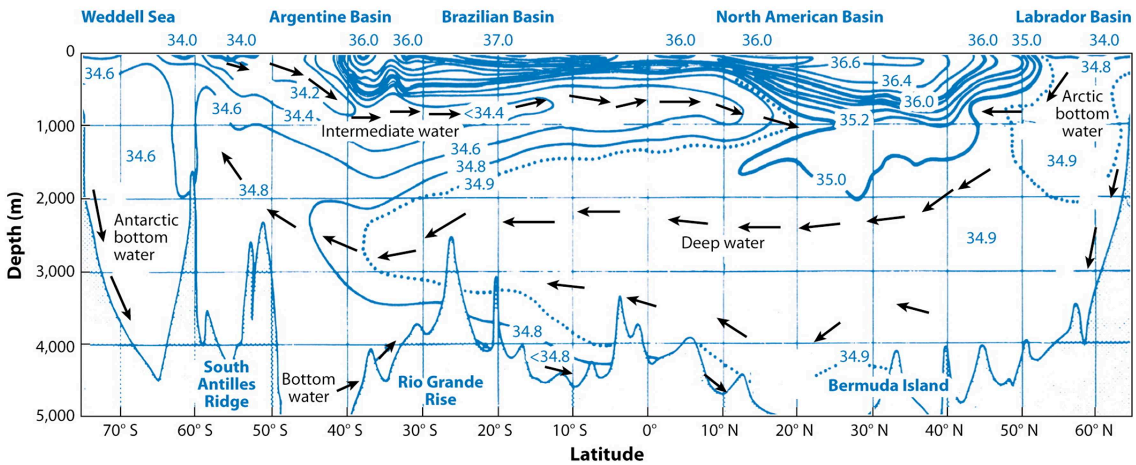

FIGURE 1 | Meridional section of salinity in the western Atlantic. Blue contours show isolines of salinity and also outline the bottom topography. Black arrows indicate directions of ocean circulation. From Lozier (2012). Copyright permission for this figure was granted by Annual Reviews.

the section. The strength of the overturning is defined as

$$MOC_z = \max_z \Psi(z) \tag{2}$$

where the subscript z on MOC_z indicates that the integration and identification of the maximum value is performed in the z-coordinate (depth). In this way, the MOC_z represents a balance between net northward (southward) flowing water above (below) the depth of maximum overturning.

At higher latitudes, there may be both northward-flowing warm water and southward-flowing cold water at the same depth. In this case, it is more useful to consider the net meridional exchange between warm (or light) and cold (or dense) water rather than shallow and deep water. To capture this, the transport streamfunction can instead be defined in density space. For the AMOC in density space, the transport through each unit area is assigned to the local density, and instead of accumulating transport-per-unit-area in depth, it is accumulated as a function of density as

$$\Psi(\rho) = \int_{\rho_{max}}^{\rho} V(\rho')\, \mathrm{d}\rho' \tag{3}$$

where V has units of transport (Sv) and is integrated by seawater density ρ for the section. The strength of the overturning in density space is then defined as

$$MOC_\rho = \max_\rho \Psi(\rho)\,. \tag{4}$$

For both MOC_z and MOC_ρ, full-depth meridional velocities across the basin are required; the AMOC estimates described below highlight observational methods for determining velocities over large swaths of the Atlantic.

1.2. History of AMOC Observations

The AMOC has a long history of observation, including the early observations based on meridional sections of watermass properties (see review in Richardson, 2008). These early watermass sections showed patterns that required watermass formation regions at high latitudes in the northern and southern hemispheres, prompting oceanographers to propose the existence of meridional watermass transport from the regions of origin. More recent efforts concentrated on direct estimates of the meridional transport across zonal sections, applying geostrophic approaches to sections of seawater density to derive velocities. The thermal wind balance used for this approach relates the vertical shear of horizontal velocity to the horizontal gradient of density in the form

$$f\frac{\partial v}{\partial z} = -\frac{g}{\rho}\frac{\partial \rho}{\partial x} \tag{5}$$

where v is meridional velocity, f the Coriolis parameter and g the acceleration due to gravity. This balance provides vertical shear of horizontal velocity, and so requires a reference velocity (either with a level-of-no-motion or level-of-known-motion) to determine absolute velocity. Meridional volume and heat transport can then be computed.

Using seawater density calculated from hydrographic sections, the MOC_z strength can be computed for an individual "snapshot" of the overturning circulation. These estimates highlighted the importance of the ocean circulation for the meridional heat transport at subtropical latitudes (e.g., Bryden and Imawaki, 2001). However, hydrographic sections are repeated relatively infrequently, providing low temporal resolution of the AMOC measurement. Bryden et al. (2005) estimated the AMOC transport at 26°N from five hydrographic sections in 1957, 1981, 1992, 1998, and 2004, showing a near-monotonic decline in the strength of the overturning (solid line, **Figure 2**). Subsequently, the RAPID mooring array at 26°N was deployed, providing sub-monthly temporal resolution of the AMOC (Cunningham et al., 2007), confirming the idea that single-section snapshots are subject to aliasing (Wunsch and Heimbach, 2006). These data revealed that the particular months in which the hydrographic

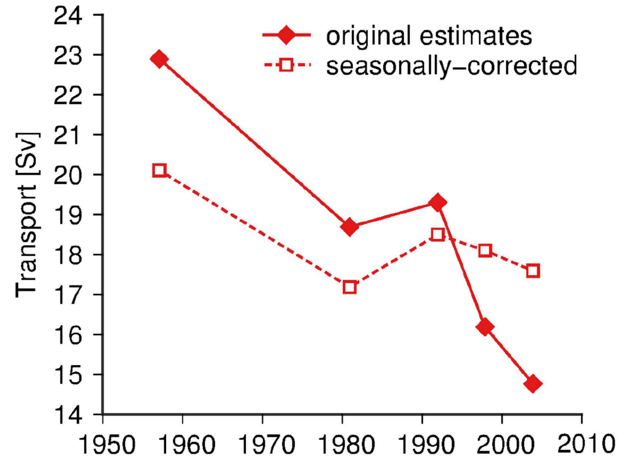

FIGURE 2 | AMOC estimate (MOC_z) from five hydrographic sections (solid), and corrected for the seasonal cycle in the AMOC (dashed). After correction for the seasonal cycle, the large, near-monotonic decrease in the AMOC strength reported by Bryden et al. (2005) was reduced to just 3 Sv of apparent change. Figure adapted from Kanzow et al. (2010).

sections were made corresponded to near the peak (1957) and the trough (2004) in the seasonal cycle, thereby aliasing the results. The seasonally-corrected section-based estimates no longer support the interpretation of a monotonic AMOC decline (dashed line, **Figure 2**). Hydrographic sections provide deep temperature and salinity measurements, and offer snapshots of the true zonal structure of the ocean circulation, but on their own, the low temporal resolution of measurements is a critical weakness for investigating AMOC variability. This example highlights the importance of continuous measurements for the AMOC, so we now define the scope of this paper: *on the continuous observation of the Atlantic overturning*. With this focus, snapshots of transport estimates based on hydrographic sections are excluded.

Continuous measurements of ocean transports also have a long history in oceanography. Much of the expertise with moored arrays and measurements that led to the development of the transbasin arrays discussed in section 2 was built on existing long-term observations of western boundary currents. However, these boundary current arrays have a fundamentally different purpose to the AMOC measurements, providing one component of the AMOC rather than a basinwide transport. Again, we have learned from the early years of the RAPID 26°N observations that there is little relationship between the strength of the deep western boundary current (DWBC) and net transbasin deep transports (Meinen et al., 2013). In the Labrador Sea, the DWBC transport is also not an adequate proxy for the AMOC (Li and Lozier, 2018). As such, western boundary current arrays are also excluded from further consideration here. Details on long-standing western boundary arrays are included in the **Supplementary Material**, with overviews of the 53°N array (Zantopp et al., 2017), Line W at 39°N (Toole et al., 2017), the pressure-equipped inverted echo sounder (PIES) measurements of the western boundary current at 26°N (Meinen et al., 2013), and the western boundary array at 34.5°S (Meinen et al., 2017). The western boundary arrays at 11°S (Hummels et al., 2015) and the NOAC array at 47°N (Roessler et al., 2015) have recently been expanded to span the Atlantic, with AMOC estimates anticipated in the near future (see **Supplementary Materials**).

2. CONTINUOUS OBSERVATIONS OF THE AMOC FROM OBSERVING ARRAYS

The standard method for making continuous observations of the AMOC is (a) to use full depth moorings to capture density profiles on either side of an ocean basin, applying thermal wind to estimate velocities across a zonal section relative to a level of no motion (e.g., McCarthy et al., 2015b; Meinen et al., 2018), (b) to combine these estimates of interior transport with direct current measurements at the boundary or boundaries and (c) with Ekman transport computed from a surface wind product. In most cases, adjustment of the reference level velocity is also made during the calculation, though the approach differs between arrays. Contrasting with the thermal wind application using hydrographic sections (section 1.2), in the moored approach it is applied over vast distances (over 1,000 km) between moored profiles of seawater density. Meridional heat and freshwater transport are further calculated using measurements of temperature and salinity across the full-depth basin (from available climatologies and float-based measurements of hydrography). Details are in Johns et al. (2011) for heat transport and McDonagh et al. (2015) for freshwater transport at 26°N, and Li et al. (2017) for OSNAP. Below, we give an overview of the observing arrays at OSNAP, 26°N, 16°N and 34.5°S (**Figure 3**).

2.1. OSNAP

In the subpolar North Atlantic, the circulation pattern is generally cyclonic, with several "lobes" filling out the Iceland, Irminger and Labrador basins. Transports have a strong barotropic component, so that the horizontal gyre circulation is largely full-depth. In addition, significant watermass transformation occurs along the cyclonic pathway of the water, so that there is a large "overturning" component in the horizontal circulation as water becomes denser along the path. For this reason, density coordinates are a more useful coordinate for OSNAP, though both MOC_z and MOC_ρ are estimated.

2.1.1. Observations

In the subpolar gyre the complex bathymetry, short Rossby radius of deformation and strongly barotropic circulation requires higher horizontal resolution of observations than in the subtropical gyre. OSNAP consists of two sections: OSNAP West extends across the Labrador Sea from the Labrador shelf near 53°N to southwestern Greenland at 60°N; OSNAP East extends from southeastern Greenland at 60°N to the Scottish shelf at 57°N, crossing the Reykjanes Ridge and the Rockall plateau. The OSNAP observing system also incorporates RAFOS float deployments in the Irminger and Iceland basins and glider surveys over the Rockhall-Hatton and Iceland basins. The OSNAP observing system was fully deployed in the summer

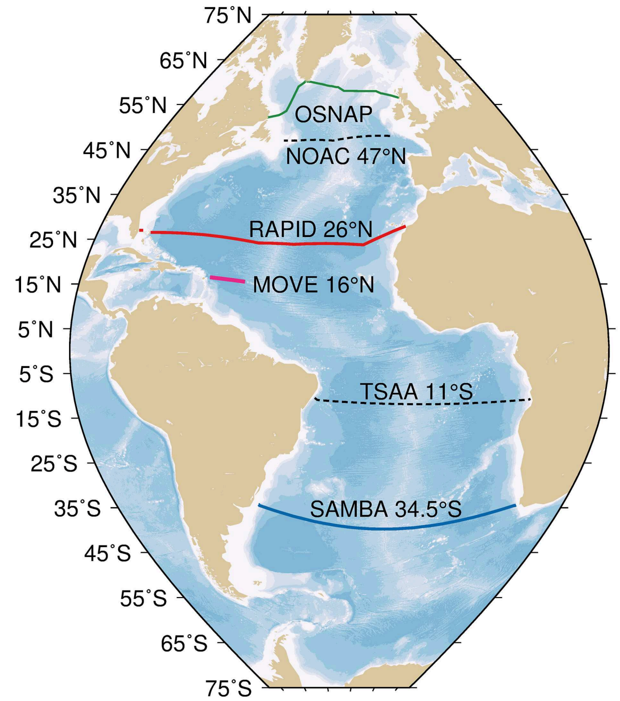

FIGURE 3 | Observing arrays in the Atlantic with AMOC transport estimates from OSNAP (green, from 2014), NOAC 47°N (black dashed, still to be produced), RAPID 26°N (red, from 2004), MOVE 16°N (magenta, from 2000), TSAA 11°S (black dashed, still to be produced), and SAMBA 34.5°S (blue, from 2009).

of 2014. The first full data recovery was 21 months later, in the summer of 2016. A second full recovery was successfully completed in the summer of 2018. The observing system remains in place with funding through at least 2020.

2.1.2. Methodology

The OSNAP array applies the standard approach at each section, combining them together to compute the full-width AMOC. Surface velocity derived from satellite altimetry is used as the reference velocity. Away from the mooring arrays, geostrophic velocities are calculated from gridded temperature and salinity fields constructed from Argo profiles, OSNAP gliders and moorings, and World Ocean Atlas 2013 climatology. The temporal resolution of the AMOC time series is 30 days. Temporal resolution for the property fields away from the arrays dictates this choice. See full details of the approach in Lozier et al. (2017) and of the methodology in Li et al. (2017).

2.1.3. Uncertainty and Limitations

OSNAP uses Monte Carlo simulations to provide an estimate of the statistical uncertainty on the AMOC strength (6% of the mean). A possible bias error of up to ~10% of the mean was found in Li et al. (2017) from a series of Observing System Simulation Experiments (OSSEs). The OSNAP observing system does not sample the shallow shelves off Labrador and Scotland (see Figure 2 in Li et al., 2017). In these regions, climatological monthly velocities from a high-resolution (1/12°) regional ocean general circulation model are used. Moving forward, a full analysis of potential bias error at OSNAP is planned as are improved estimates for inshore properties and velocities.

2.1.4. Results

The first set of results show that the majority of the overturning occurs north of OSNAP East, where northward flowing warm and salty Atlantic waters of subtropical origin are replaced with cooler, fresher southward flowing waters moving along the western boundaries of the Iceland and Irminger basins (Lozier et al., 2019). The contribution of overturning in the Labrador Sea (north of OSNAP West) is a factor of seven smaller than that north of OSNAP East.

2.2. RAPID 26°N

In the subtropical North Atlantic at 26°N, the circulation pattern consists of an anticyclonic subtropical gyre, a strong northward western boundary current (top 1,000 m) largely confined between Florida and the Bahamas, and southward flowing North Atlantic Deep Water (NADW, 1,000–5,000 m). Below this, there is a small amount of weakly variable northward flowing Antarctic Bottom Water (1–3 Sv, Frajka-Williams et al., 2011) west of the Mid-Atlantic Ridge (MAR). Zonal gradients and the zonal tilt of isopycnals are relatively small (compared to the subpolar gyre), so that most of the net mass and heat transport can be accurately captured in depth space (MOC_z). Due to the large AMOC strength and large vertical gradients in temperature, the northward heat transport by the ocean circulation is large at this latitude.

2.2.1. Observations

The combined RAPID/MOCHA (Meridional Overturning Circulation and Heat-flux Array) observations consist of a boundary array with current meters in the west on the continental shelf and upper slope (between 77°W and 76.75°W, east of the Bahamas), and tall moorings west and east of the Mid-Atlantic Ridge or MAR (at 24°N) and along the eastern boundary (toward the Canary Islands at 28°N). Florida Current transport measured electromagnetically on an out-of-use submarine telecommunications cable are also used. The cable measurements and calibrations are part of the Western Boundary Time Series (WBTS) project, with several calibration cruises annually. The RAPID/MOCHA/WBTS observing system was fully deployed in March 2004. Data are processed and made available every ∼18 months. The array remains in place with funding presently in place through at least 2020.

2.2.2. Methodology

Geostrophic velocities are initially referenced to zero at the bottom, then the barotropic or external transport is added uniformly at each longitude and depth. Net transports use the interior geostrophic, boundary and Ekman components as well as the Florida Current. See full details of the calculation in McCarthy et al. (2015b).

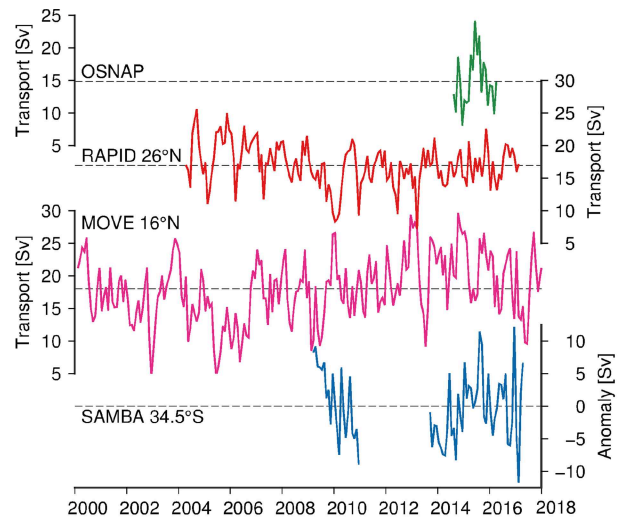

FIGURE 4 | Monthly values of MOC_z transport from four observing arrays: OSNAP (green), RAPID 26°N (red), MOVE 16°N (magenta) and SAMBA 34.5°S (blue). For SAMBA, the transports are shown as anomalies (see section 2.4). The respective means are given by the black dashed line (zero in the case of SAMBA).

2.2.3. Uncertainty and Limitations

Areas inshore of the 1,000 m isobath on the eastern boundary are not instrumented, as well as deep areas east of the EB1 mooring at the base of the eastern continental slope and either side of the MAR. The surface 100 m is often unsampled, depending on the height of each subsurface mooring during each deployment. Gaps in the vertical are extrapolated, while "bottom triangles" are neglected. The residual calculation for the uniformly distributed barotropic flow (which is on the order of 10 Sv, Frajka-Williams et al., 2018) represents one of the larger areas of uncertainty in the calculation, as the choice of where to distribute the compensatory flow has some influence on the vertical structure of the overturning streamfunction.

2.2.4. Results

Over the April 2004–February 2017 observational record, the mean and standard deviation of the overturning transport is 17.0 ± 4.4 Sv (**Figure 4**). The seasonal cycle has a peak-to-peak amplitude of 4.3 Sv (maximum northward transport in October). Interannual variations include a notable dip of roughly 30% in 2009/10, and the period following about April 2008 has been fairly stable with an average transport roughly 2.7 Sv less than was observed in April 2004–April 2008 (Smeed et al., 2018).

2.3. MOVE 16°N

In the tropical North Atlantic at 16°N, the region east of the Caribbean and west of the MAR is characterized by the southward-flowing DWBC, and episodic and northward flowing waters and northward moving eddies along the Antilles islands. Most of the northward flow of the overturning circulation occurs in the Caribbean, while east of the MAR it is relatively quiescent. Below the DWBC, there is some northward flowing Antarctic Bottom Water, primarily west of the MAR. While the MOVE array does not span the full basin width at 16°N, it is intended to provide the time-varying AMOC and so is included here.

2.3.1. Observations

At 16°N, the observational approach uses full height moorings and boundary arrays but only over the region west of the MAR (15.5°N, 51.5°W) and east of Guadeloupe (16.3°N, 60.5°W), with direct velocity measurements on the western continental slope (just west of 60.5°W). Recent deployments of the dynamic height moorings are full-height (to within 100 m of the surface), while earlier deployments were only below 1,000 m. The MOVE array was initially deployed in early 2000 and has been in operation ever since. The array remains in place with funding renewing annually.

2.3.2. Methodology

Transports between 60.5°W and 51.5°W are calculated using geostrophy, referencing the dynamic height profiles to zero flow at depth (4,950 dbar). This level coincides with the interface depth between northward-flowing Antarctic Bottom Water and southward-flowing NADW. The AMOC at 16°N is calculated as the deep southward-flowing transport (60.5–51.5°W) between 1,200 and 4,950 dbar. The transport is computed as the sum of the boundary and internal components, from current meters and dynamic height, respectively. While an "external" component can be derived from bottom pressure observations at the western and eastern edge of the array (Frajka-Williams et al., 2018), drift in the measurement precludes analysis of low-frequency variability and so these pressure observations are not included in the AMOC estimate. See Send et al. (2011) and references therein for more details of the methodology.

2.3.3. Uncertainty and Limitations

The array explicitly assumes that the southward-flowing NADW is found in the western half of the basin and neglects transport east of the MAR. Further, no measurements are included in the Caribbean as the MOVE array focuses on the southward-flowing deep transports (absent in the Caribbean). Acknowledging uncertainties associated with the choice of reference level, the array is designed to measure the variability of the overturning rather than its absolute value.

2.3.4. Results

Over the period February 2000–June 2018, the mean and standard deviation of the daily values are 18.0±5.8 Sv (**Figure 4**). The seasonal cycle has a range of 4.8 Sv and peaks in July. Over this period, there is a strengthening tendency of 0.25 Sv/year. This represents a reversal of the declining tendency of 20% identified between Jan 2000–June 2009, due primarily to deep changes at the western flank of the MAR (Send et al., 2011). More recently, over the 2004–2017 period, the circulation changes at 16°N showed an intensifying AMOC while the observations at 26°N showed a weakening AMOC, associated with differences in the treatment of the reference velocity in the geostrophic calculation (Frajka-Williams et al., 2018).

2.4. SAMBA 34.5°S

In the South Atlantic, the large meridional gap between the African and Antarctic continents provides a significant crossroad for watermass exchange between the eastward flowing Antarctic Circumpolar Current as well as between watermasses of the subtropical Indian and South Atlantic gyres (de Ruijter et al., 1999; Speich et al., 2006). This Indian to Atlantic transfer forms an important part of the source waters to the northward flowing warm and saline waters in the Atlantic, taking place through Agulhas Leakage (Boebel et al., 2003). In addition, the salt and freshwater fluxes in the South Atlantic are key to understanding potential feedbacks in AMOC variability (Dijkstra, 2007).

2.4.1. Observations

Since 2009, moored observations using PIES have been made offshore of South America just north of the separation of the Brazil Current from the coast, with later augmentations to the western array including ADCP and bottom pressure recorder instruments being added up on the continental upper slope/shelf in December 2013 and current-equipped PIES (CPIES) improving the horizontal resolution in 2012. From 2008 to 2010 a pilot array of CPIES was in place offshore of Africa, and since 2013 a more complete array of CPIES and dynamic height/current meter moorings has been built between Walvis Ridge (near the prime meridian) and the South African coast. The array remains in place, with future augmentations in the works, and funding of all of the major components is in place through at least 2020.

2.4.2. Methodology

Initial AMOC estimates from SAMBA have been based on the longest available time series, i.e., the PIES and CPIES at roughly 1,350 dbar of water, on the west and east side of the basin respectively. The PIES/CPIES travel time measurements are combined with hydrography-derived look-up tables via the Gravest Empirical Mode (GEM) method to produce daily dynamic height profiles at the west and east boundaries for estimating the geostrophic velocity shear. The PIES/CPIES bottom pressure measurements are then used to estimate the time-varying portion of the barotropic reference velocity (and hence no 'residual' zero net flow assumption is made here). Meridional Ekman transport is estimated from gridded observation-based winds (Cross-Calibrated Multi-Platform). Because the bottom pressure sensors used in this way can only estimate the time-variability of the barotropic velocity, the time-mean reference velocity is included from a numerical model (Ocean for the Earth Simulator, OFES). The time-mean of the OFES model output is also used to estimate the meridional transports inshore of the 1,350 dbar isobaths on either side of the basin. See full details of the methodology in Meinen et al. (2018).

2.4.3. Uncertainty and Limitations

The use of a time-mean reference velocity from a model means that the observations at 34.5°S provide only the time-variability of the AMOC rather than an observational mean. In addition, measurements inshore of 1,350 dbar on both boundaries are unsampled, relying on model velocities again.

TABLE 1 | Basic statistics for the time series of AMOC strength at the four latitudes where the time series are available.

	Time period	Mean [Sv]	Standard deviation [Sv]
OSNAP	Sep 2014–May 2016	14.9	4.1
RAPID 26°N	Apr 2004–Feb 2017	17.0	3.3
MOVE 16°N	Feb 2000–Jun 2018	18.0	4.7
SAMBA 34.5°S	Mar 2009–Apr 2017	14.6	5.4

Standard deviations are based on monthly estimates over the periods listed in the table. Note that the MOC is reported as MOC_ρ for OSNAP, but as MOC_z for the other latitudes. This is because the MOC in density space is the preferred metric at the OSNAP array. The overturning in depth space at OSNAP is 8.0 ± 0.7 Sv.

2.4.4. Results

The 34.5°S array is in a complicated area where the AMOC is highly variable, with both western and eastern boundary currents contributing to the AMOC variability at a variety of timescales (Meinen et al., 2018). On interannual timescales, eastern boundary density changes dominate the AMOC variations, and both baroclinic and barotropic changes at both boundaries are important on seasonal timescales (Meinen et al., 2018), with strong intra-seasonal buoyancy anomalies driven by migrating eddies (Kersalé et al., 2018). The AMOC has a peak-to-peak range of 54.6 Sv (on daily means, monthly means shown in **Figure 4**).

2.5. Intercomparisons Between Latitudes

With several multi-year measurements of the AMOC at different latitudes, there is the potential to investigate the large-scale circulation spanning multiple latitudes. The average strength of overturning differs among latitudes, though the individual estimates are computed over different time periods (**Table 1**). As a consequence, the standard error of the mean (standard deviation divided by number of years of the time series) decreases with an increasing length of the time series (**Figure 5**). There may be a latitudinal dependence to the variability of the AMOC, with higher variance in the South Atlantic than the North Atlantic. However, intercomparisons are limited by the length of the time series; when the standard deviation is computed over the OSNAP period only, they are 4.1 Sv, 2.5 Sv, 4.2 Sv, and 4.7 Sv from north to south.

Evaluation of the seasonal cycles of the AMOC between latitudes found that the seasonal cycle of the non-Ekman component of the overturning is 180° out-of-phase (Mielke et al., 2013) between 26°N and 41°N (see section 3.3). Deep transport variability has been compared between 26°N and 16°N, however it was determined that because the MOVE array does not span the entire basin width, an appropriate comparison can only be made by focusing on the westernmost profiles at the two latitudes (Elipot et al., 2014), as the western boundary dynamic height profile captures much of the deep transport (and AMOC variability) at 26°N. On seasonal and interannual timescales, variability is phased between latitudes and related to wind-forcing associated with, e.g., the North Atlantic Oscillation (Elipot et al., 2017). On interannual and longer timescales, low frequency deep density changes are consistent at both 26°N and 16°N in sign and magnitude, with changes occurring first at 26°N

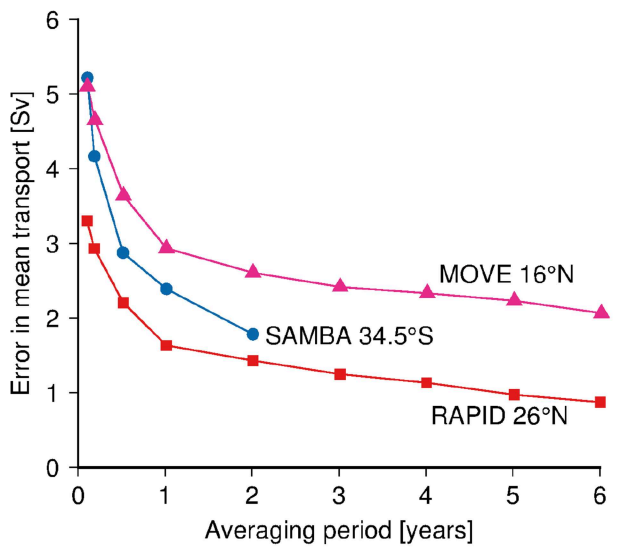

FIGURE 5 | Uncertainty on the estimate of the mean AMOC based on averaging for a certain number of years of the AMOC time series at RAPID 26°N (red squares), MOVE 16°N (magenta triangles) and SAMBA 34.5°S (blue circles). Note that the limit in the error will be bounded below by the intrinsic variability in the time series, which is higher at 16°N than the other two latitudes (see **Table 1**).

and 7 months later at 16°N (Frajka-Williams et al., 2018). Since about 2009, the deep salinities at the western boundary of both latitudes have freshened, resulting in a thicker dynamic height and reducing the basin-wide tilt of isopycnals. Frajka-Williams et al. (2018) further showed that choices in methodology, i.e., the application of a reference level velocity to the geostrophic shear derived from dynamic height, can have a dominant role in the low-frequency variability of the derived AMOC time series.

3. ALTERNATE APPROACHES FOR DIRECT AMOC ESTIMATES

3.1. Bottom Pressure Approaches

The application of the thermal wind balance using full-height mooring data as outlined in section 2 provides geostrophic transport estimates for an oceanic section with vertical walls. As a consequence, direct measurements of velocity are required on boundaries where the ocean walls are sloped. Hughes et al. (2013) show how the thermal wind balance can be extended to obtain geostrophic transport from vertical gradients of ocean bottom pressure (OBP) along sloping boundaries at a given latitude. The RAPID Western Atlantic Variability Experiment (WAVE) at 42–43°N showed that vertical gradients of OBP can be determined from near-bottom velocity and density from moorings (Hughes et al., 2013).

Model studies indicated that the western boundary OBP signal dominates over the eastern boundary signal for determining trans-basin geostrophic transport (Bingham and Hughes, 2008; Hughes et al., 2018). Investigations using the RAPID 26°N array data confirmed that the western boundary contribution to the geostrophic transport in the 1,000–4,000-m layer (relative to 1,000 m), captures more than 50% of the variance of MOC_z at periods longer than 230 days (Elipot et al., 2014). The method was directly applied near 39°N using data from the Line W western boundary current array and near 41°N using data from RAPID WAVE (Elipot et al., 2014). The resulting geostrophic transports below 1,000 m using only data from the western boundary showed good agreement with an independent satellite and hydrography based MOC_z estimates near 41°N (Willis, 2010). The advantage of this method over the full-height arrays is that these moorings are smaller and less expensive, making them easier to deploy.

3.2. Satellite-Only Methods to Estimate Ocean Circulation

Satellite-based estimates of ocean circulation are not limited to individual latitudes. Geostrophic balance can be applied to both sea level anomaly (SLA from altimetry) and ocean bottom pressure (from gravimetry) to estimate velocities, where horizontal gradients in pressure drive horizontal flow perpendicular to the gradient. The relationship between SLA and the time-varying AMOC in numerical models (Bingham and Hughes, 2009, and others) suggested that SLA could be used to generate a proxy for the AMOC. However, comparisons between RAPID 26°N transports and SLA demonstrated that near surface (0–2,000 m) seasonal variations in steric height were large and under-sampled by subsurface moorings, confounding the use of SLA for ocean transports (Ivchenko et al., 2011). Using longer *in situ* records and removing a seasonal climatology, a SLA-based proxy of the AMOC at 26°N was found to recover 80% of the upper mid-ocean transport variability (transbasin transport between the Bahamas and Canary Islands, in the top 1,100 m). When combined with the Florida Straits transport and meridional Ekman transport from winds, this approach explains 90% of the interannual variability of the AMOC over the period April 2004–March 2014 (Frajka-Williams, 2015).

Using OBP from the Gravity Recovery and Climate Experiment (GRACE), Landerer et al. (2015) applied geostrophy to OBP between 3,000 and 5,000 m at 26°N (west and east) to calculate deep ocean transports. The transport variability agreed well with the RAPID 26°N observations (explaining 67% of the variance in the LNADW layer at 26°N) after smoothing both with a 9-point Lowess filter. Both of these investigations suggest that, at least in the subtropical gyre at 26°N at sub-decadal timescales, satellite altimetry and gravimetry can be used to make meaningful estimates of ocean transports over large spatial scales. However, the SLA method assumes a relatively stationary relationship between dynamic height profiles and SLA which would be expected to change as watermass properties and distributions change (e.g., due to buoyancy forcing). The gravimetry-based estimates have uncertainties at long timescales, associated with the application of the glacial isostatic adjustment models, limiting their use (for now) to investigating monthly-to-interannual variability.

3.3. Satellite + Hydrography Methods to Estimate Overturning

To combat the limitation of SLA-only approaches—that subsurface velocity structure cannot be determined—multiple efforts have combined SLA with hydrography to estimate velocity. Willis (2010) used SLA and hydrography from Argo floats to estimate the time-varying volume transport above 1,130 m in the North Atlantic. Applying the method in a numerical model, he found that the method captured the AMOC variability at 41°N, just north of where the Gulf Stream separates from the coastline. This was an important feature of the location, as the water velocities on the continental slope (water depths shallower than 2,000 m, typically not sampled by Argo floats) were weak, so that errors resulting from missing data are small.

In the South Atlantic, various methods have been used to combine SLA and subsurface hydrography. Schmid (2014) combined hydrography with altimetry to construct a three-dimensional geostrophic velocity field on a monthly basis in the subtropical South Atlantic. Majumder et al. (2016) further extended the velocity field to the bottom using hydrographic climatologies. They found that the MOC and meridional heat transport are strongly correlated between 20–35°S over the 2000–2014 period. Dong et al. (2015) used a climatological relationship between SLA and temperature and salinity profiles to construct synthetic temperature and salinity profiles from time-varying SLA between 20 and 35°S. They found that interannual variations in the AMOC south of 20°S are dominated by geostrophic variations. In the North Atlantic, Mercier et al. (2015) constructed an AMOC transport in the eastern subpolar gyre (1993–2017) by combining time-varying altimetry with Argo hydrography, and verifying the result with hydrographic section estimates (**Figure 6**).

Hydrographic sections are typically occupied every 5 years, meaning that they will not resolve the high frequency variations that have been identified by moored observations. Float-based hydrography lacks resolution and coverage in waters shallower than 2,000 m (near boundaries), particularly when compared to the resolution and high frequency sampling of moored observations (section 2.6). However, calculations using hydrography combined with altimetry can be applied globally and retroactively, and so have the potential to fill the gap between individual mooring arrays, with the caveat that near-boundary measurements may be sparse compared to moored approaches.

4. INDIRECT APPROACHES FOR OBSERVATION-BASED AMOC ESTIMATES

4.1. Budget/Residual Approaches

Ocean heat content (OHC) in a zonally-integrated, meridionally bounded volume of the ocean varies due to inputs from the atmosphere, or meridional heat transport *MHT* into (out of) the region from the south y_s (north y_n) by the ocean. This can be estimated as

$$OHC(t) - OHC(t_0) = \int_{t_0}^{t} F_s(t') + MHT(y_s, t) - MHT(y_n, t)\, \mathrm{d}t' \tag{6}$$

where F_s are the surface fluxes over the region. This approach was used in Kelly et al. (2014) using observed OHC and surface fluxes. From this, they were able to derive meridional heat transport divergence [in this formulation, $MHT(ys,t) - MHT(yn,t)$] at a range of latitudes in the Atlantic. Their calculation of heat flux divergence showed a remarkable coherence across latitudes through the South Atlantic which did not hold in the North Atlantic. As they could only infer the heat flux divergence, a time series of known meridional heat transport must be provided for one latitude in order to estimate the heat transport rather than the transport divergence at all other latitudes. Repeating the calculation for both heat and freshwater fluxes, Kelly et al. (2016) produced a time series of meridional heat transport anomalies at 26°N using the Argo-altimetry based estimates at 41°N to anchor their fluxes (Willis, 2010). This approach adds value to a time series of heat transport at a single latitude, and enables a wider view of the meridional coherence or divergence of the AMOC and associated transports.

A second residual approach has been applied by balancing the Earth's energy budget locally (Trenberth and Fasullo, 2017, 2018), where atmospheric heat flux divergence ($\nabla \cdot F_A$) and top of the atmosphere (R_T) radiation are further considered, allowing the derivation of surface fluxes (F_s) as

$$\nabla \cdot F_A = R_T + F_S \tag{7}$$

which reduces the problem of energy budget imbalance in reanalyses. Surface fluxes are combined with ocean heat content (determined from *in situ* observations) to estimate meridional heat transport

$$MHT(\phi) = \int_{\phi}^{90} \left[F_s + \frac{dOHC}{dt} \right] d\phi \tag{8}$$

at each latitude ϕ. From this approach, they find the largest uncertainties lie with the OHC estimates used in their calculation, which suffered from spurious signals below 1,000 m. In general, residual approaches are limited by the present generation of Argo floats which are typically pressure-rated to 2,000 dbar. Despite this, they showed a successful reproduction of the reduction in northward heat transport at 26°N in 2009/10.

4.2. State Estimates

State estimates or ocean reanalyses provide another method to determine the time-varying AMOC. State estimates use forced ocean models and assimilate observed data (e.g., *in situ* temperature and salinity, SST, altimetry), producing a simulated ocean state that is closer to the observed state. Methods of assimilation vary (Balmaseda et al., 2015; Stammer et al., 2016; Carrassi et al., 2018), ranging from simple relaxation, optimal interpolation, Kalman filtering to three-dimensional variational assimilation (3DVar), all of which are sequential or filtering methods used in ocean analysis or reanalysis (the observations only impact the ocean state in the future). Methodologies that are often called "state estimation" rather than "data assimilation" do not directly change ocean fields,

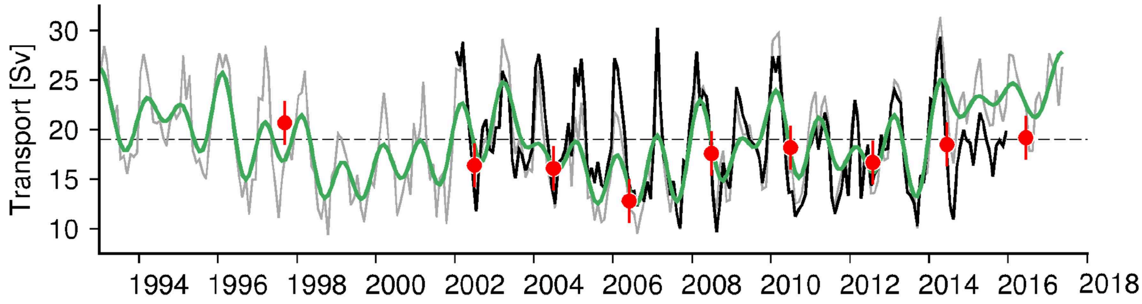

FIGURE 6 | A time series of AMOC transport (MOC_ρ) at the OVIDE section (eastern subpolar gyre: Portugal to Cape Farewell) for 1993–2017, constructed from altimetry and hydrography. The gray line is from altimetry combined with a time-mean of Argo velocities; the green curve is low-pass filtered using a 2-year running mean. The black curve is from altimetry and Argo. Red circles are estimates from OVIDE hydrography with associated errors given by the red lines. The mean of the gray curve is given by the black dashed line (Updated from Mercier et al., 2015).

but rather adjust surface forcings and ocean mixing parameters to achieve a best, continuous fit to observations (e.g., 4DVar, see Forget et al., 2015). Transports, e.g., the AMOC strength, can then be calculated from the state estimate's full-depth velocity fields. However, care must be taken that the AMOC is suffciently and correctly constrained by the observations since data assimilation or model drifts can lead to incorrect results. Hence more direct MOC estimations are needed to validate MOC estimates derived through assimilation or state estimation (e.g., Evans et al., 2017).

Improvement of the mean AMOC strength has been found in state estimates over forced ocean models (Balmaseda et al., 2007), possibly more so in higher resolution models (Tett et al., 2014). However the improvement of AMOC variability is found to differ between studies. Munoz et al. (2011) and Karspeck et al. (2017) found substantial variations between reanalysis AMOC strengths for the period from 1960 onwards, with more spread in the state estimates than forced ocean models. These results suggest that the state estimates do not always provide reliable estimates of the AMOC changes. On the other hand, several studies found good agreement between state estimates and the RAPID 26°N AMOC on seasonal and interannual timescales (Baehr et al., 2009; Haines et al., 2012; Roberts et al., 2013; Wunsch and Heimbach, 2013; Köhl, 2015; Jackson et al., 2016). One state estimate was then used to diagnose the causes of the temporary AMOC weakening in 2009–10 (Roberts et al., 2013) and its decadal decline (Jackson et al., 2016). The likely reason why these state estimates show agreement amongst themselves and RAPID is that they focus on the satellite period only when there are more observational constraints. The AMOC components (for instance the split between the Florida Straits and upper mid-ocean transports at 26°N) are more difficult to attain (Roberts et al., 2013; Köhl, 2015; Jackson et al., 2016; Evans et al., 2017), suggesting that the AMOC strength may be captured through a large-scale constraint rather than in resolving the detailed circulation. Understanding what creates this large-scale constraint could be important for improving the reanalyses and monitoring the AMOC. Attempts have also been made to assimilate the RAPID 26°N observations themselves, either through direct assimilation of the moored profiles of temperature and salinity (Baehr, 2010; Stepanov et al., 2012; Köhl, 2015), using covariances to derive a large-scale temperature and salinity signal from the moored profiles and then assimilating this signal (Hermanson et al., 2014; Thomas and Haines, 2017), or assimilating the 26°N transports (Baehr, 2010; Köhl, 2015).

State estimates provide continuous AMOC estimates over the whole basin, and can enable deeper investigations into the mechanisms driving AMOC variability. The quality of state estimates can be limited by the lack of observations near coasts, and by insufficient model resolution to resolve boundary currents. Poorer observational coverage prior to the satellite and Argo period may notably restrict their utility back in time.

4.3. Fingerprints and Proxies

Changes in the AMOC strength have been linked to changes in essential ocean variables, including SST and subsurface temperature (Zhang, 2008), SLA (Bingham and Hughes, 2009; Frajka-Williams, 2015), and deep density gradients (Baehr et al., 2008; Zanna et al., 2011). These AMOC fingerprints—defined as a "coherent pattern of response to the ocean circulation" (Alexander-Turner et al., 2018)—can enable prediction or attribution of SST or SLA variations in response to AMOC changes. They have also been used to derive proxies for the AMOC strength by identifying the fingerprint of the AMOC on SST changes, then using the longer SST record to derive the associated AMOC strength back in time (Lopez et al., 2017; Ceasar et al., 2018). Such proxies can provide a longer term context within which to understand present-day variations. However, while fingerprints are often identified using a linear regression between AMOC strength and the fingerprint amplitude, the relationship between the AMOC and fingerprint variable may be non-stationary, meaning that the relationship between AMOC and fingerprint variable changes in time (Alexander-Turner et al., 2018). In addition, there can be multiple drivers of SST variations, meaning that observed variations in SST and AMOC could both be symptoms of an external forcing, complicating attribution (Booth et al., 2012; Zhang et al., 2013, 2016; Clément et al., 2014).

Tide gauge sea level records may be less influenced by atmospheric heating than SST. There is a long history of using tide gauge sea level records on the US East Coast to infer changes in the Florida Current, an AMOC component, based on geostrophic balance (Iselin, 1940; Montgomery, 1941; Hela, 1952). Recent observational studies show significant correlations between US East Coast sea level and the AMOC (Sallenger et al., 2012), Gulf Stream (Kopp, 2013), and AMOC and North Atlantic Oscillation (Goddard et al., 2015), on a variety of timescales from intra-seasonal to multi-decadal. McCarthy et al. (2015a) argue that the coastal sea level difference between the South Atlantic Bight and Mid-Atlantic Bight serves as an index of midlatitude meridional heat flux in the North Atlantic, and that the time integral of this coastal sea level index provides a measure of subpolar North Atlantic Ocean heat content. However, changes in sea level along the US East Coast may also be induced by longshore winds, barometric pressure or river runoff, obscuring the relationship to the large-scale ocean circulation on interannual and longer time scales (e.g., Andres et al., 2013; Woodworth et al., 2014; Piecuch and Ponte, 2015; Piecuch et al., 2018). Moreover, climate modeling studies show that the relationship between sea level and AMOC transport depends on the timescale of variability in question (Little et al., 2017). Confidence in these studies could be improved by developing understanding of the physical mechanisms mediating the relationship between the AMOC and coastal sea level before inferring AMOC variability (e.g., Minobe et al., 2017).

5. GAPS IN OBSERVING

Above, we outlined efforts to observe or estimate the strength of the AMOC and associated heat or freshwater transports. However, a narrow focus on these aims leaves gaps in observing that may limit analysis of AMOC-related mechanisms and impacts.

5.1. Paucity of Observations on the Shelf-Break and in the Deep Ocean

Instrument risk is high in shallow shelf seas (e.g., the shelves around Greenland and Labrador). As a consequence, observational approaches using moored observations tend to leave gaps in these regions, adding uncertainty particularly in the freshwater transport estimates in these regions. In the open ocean, the largest signals of transport variability to-date are found in the upper ocean; on longer timescales, changes are anticipated at depth. The deep ocean is relatively undersampled, as the Argo float profiling array concentrates on the top 2,000 m. Full-depth hydrographic measurements remain the primary source of deep ocean observations, but are sparse in time. Deep changes recently observed at 26°N and 16°N are responsible for low frequency circulation changes (Frajka-Williams et al., 2018) but are barely above the limits of instrumental accuracy (McCarthy et al., 2015b). Observing efforts that rely on upper ocean and surface intensified measurements, or boundary-only measurements at depth, may fail to capture the low frequency, deep density variations across the Atlantic basin.

5.2. Interior Pathways

While boundary-focused observations capture the transbasin baroclinic transport, they do not account for interior circulation pathways. Tracer measurements highlight that the DWBC is not the only conduit of newly formed deep waters from high latitudes into the rest of the ocean basins (LeBel et al., 2008). Recent Lagrangian studies using real and numerical floats have shown that, in the North Atlantic, there are 'interior pathways' of circulation that water parcels likely follow, with the intermediate depth water masses (e.g., Labrador Sea Water at 1,500 m) moving offshore at the Grand Banks and spreading down the Mid-Atlantic Ridge as well as within the DWBC (Bower et al., 2009; Lozier et al., 2013). Likewise, a recent compilation of observations and modeling output has revealed interior pathways for Iceland Scotland Overflow Water, including a southward pathway along the eastern flank of the Mid-Atlantic Ridge (Zou et al., 2017). These pathways are not explicitly resolved in transbasin geostrophic arrays, but are important to understanding the spread of watermasses and tracers (including carbon) and advection timescales of anomalies from high to low latitudes (Lozier et al., 2013; Le Bras et al., 2017).

5.3. Carbon, Nutrients and Oxygen Transports

The North Atlantic is a sink of atmospheric CO_2 taking up roughly 40% of the global ocean uptake of carbon from the atmosphere (Takahashi and Coauthors, 2009). A cooling ocean such as the North Atlantic takes up carbon from the atmosphere through the solubility pump. The vertical mixing resulting from the loss in surface buoyancy brings nutrient-rich waters to the surface fueling biological productivity, driving further carbon into the deep ocean via the biological carbon pump. New efforts are underway to estimate the time-varying transport of nutrients and carbon, to develop understanding in the role of the AMOC in North Atlantic carbon uptake. To make time-varying measurements of chemical properties, the Atlantic BiogeoChemical Fluxes (ABC Fluxes) observational programme has added oxygen sensors and samplers to the moorings at 26°N, while oxygen, pH sensors and water samplers were added to the OSNAP Rockall Trough array, and oxygen and pH sensors added to the 53°N array, enabling time-series of biogeochemical properties from transport arrays. The ABC Fluxes 26°N project has estimated time-series of ocean transports of anthropogenic carbon and inorganic nutrients using observations from the RAPID 26°N array, Argo floats and GO-SHIP sections, and applying multiple linear regression between parameters. Preliminary results have shown that the AMOC volume transport at 26°N has a primary role in setting the strength and variability of the property transport across 26°N; that the transport is a first order component of the carbon and nutrient budgets in the North Atlantic; and that AMOC variability also drives significant variability in the uptake of carbon (both solubility and biological pumps) through its control on upper ocean heat content and stratification in the North Atlantic.

6. FUTURE OBSERVATIONAL APPROACHES

6.1. Sustaining AMOC Observations

Our purpose in observing the AMOC is to develop understanding of the oceanic volume, heat and freshwater transport, its variability and dynamics, and response to and feedbacks on the climate system. Importantly, we are concerned with the present, the recent past (∼50 years), and how transport variability and mechanisms may change in a changing climate. However, the AMOC variability and its imprint on essential ocean variables differs among global circulation models and coupled climate models. Global models struggle to represent small scale processes—including overflows from the Nordic seas, open-ocean deep convection and narrow boundary currents—and deep ocean circulation in general. In view of the limitations of general circulation models, observations are critical to understanding the mechanisms of AMOC variability. Pressing questions remain as to the role of the AMOC in Atlantic Multidecadal Variability, its role in generating or preconditioning the "cold blob" in the North Atlantic, and how AMOC-generated ocean heat content anomalies influence phenomena with societal relevance including hurricanes, heat waves and regional sea level change. In particular, AMOC observations are needed to investigate

1. The AMOC transports, their variability and meridional coherence,
2. The AMOC response to surface forcing and overflows,
3. The influence of meridional heat transport divergence on ocean heat content, air-sea fluxes, and sea level,
4. The influence of meridional freshwater transport on AMOC transports and variability, and
5. The relationship between interior pathways, boundary currents and the AMOC.

as a function of time-scale (seasonal, interannual, decadal and longer) and latitude bands (subpolar, subtropical, and equatorial). Sustained and widespread observations allow mechanistic understanding to be developed and the attribution of signals to causes. This will improve the monitoring system allowing a greater understanding of the extent and likely impacts of detected signals. Such understanding also helps to improve models used for seasonal-to-decadal and climate predictions.

6.2. Synthesis of Existing AMOC Observations

Moored observations of the AMOC strength (section 2) have profound advantages over the previous methods (using hydrographic sections or western boundary current arrays). These include:

1. High time resolution observations (~daily) combatting the previous problem of aliasing of large amplitude, high frequency variability onto lower frequencies,
2. Near boundary measurements for a complete transbasin estimate, reducing the influence of large-amplitude, mid-basin mesoscale variability,
3. Full-depth observations spanning the full basin width, enabling the use of a zero net mass transport constraint on the choice of reference level for geostrophic velocities.

These observations have provided detailed and robust insights into ocean circulation variability, but they are limited to individual latitudes. How do we reconcile the AMOC variability at individual latitudes (section 2.5) and generate broader understanding of AMOC-related transports and divergence and its role in the climate system?

Direct observational approaches (moored or satellite+hydrography) can be used in combination to quantify or reduce uncertainties due to instrumental accuracy, sampling or methodology. The combination of satellite data with *in situ* moored observations, with or without concurrent bottom pressure measurements or Argo float profiles may provide an independent check on moored observations (Williams et al., 2015). Subsampling moored observations could be used to validate satellite and Argo approaches—checking how their reduced temporal resolution affects confidence. Observing system simulation experiments, where numerical models are subsampled according to observational sampling, can further be used to evaluate uncertainties, provided the models are sufficiently representative. Ocean state estimates provide a synthesis of numerous data sets, enabling mechanistic interpretation of observed signals (e.g., Evans et al., 2017). Synthesis between direct observational approaches and residual approaches offer new potential for investigating the sensitivity of the AMOC to freshwater inputs from the cryosphere, interactions between the AMOC and atmosphere through air-sea fluxes, or longer timescale variability in the climate system (e.g., the Atlantic Multidecadal Variability).

Synthesis between observations and numerical models is essential to assess and advance the fidelity of models. The concept of a common framework into which both observations and models can be mapped and subsequently analyzed has emerged under the term AMOC metrics. Such comparisons can be prohibitively difficult for individual researchers due to data and infrastructure barriers; incommensurability; and social and scientific barriers. A new project "AMOC Metrics" aims to address these impediments, primarily as a service activity, by (i) promoting the use of metrics in intercomparison projects that are relevant to advancing understanding of the Atlantic Ocean state, circulation, and influence; (ii) reflecting the science advances being driven by the AMOC community; (iii) facilitating the joint interpretation of models and data; and (iv) promoting objectivity in model-intercomparisons. The major deliverable of the project is a set of value-added AMOC-related metrics with associated diagnostics tools and curation for the use of the broader community. To provide the most appropriate observations vs. model comparisons, the tools / packages will enable calculation of transports from the models using methods that are analogous to what observations use, initially focusing on individual latitudinal arrays.

6.3. Evaluating Potential of AMOC Observation Systems

Below, we outline some criteria to consider when evaluating the potential of future AMOC observation systems. These are based on the variability observed by the present arrays, as well as future changes that are anticipated based on numerical simulations but that are not apparent or dominant in the observations.

6.3.1. Regions

Studies of meridional coherence based on observations showed an apparent lack of coherence even just within the North Atlantic subtropical gyre on seasonal timescales (Mielke et al., 2013; Elipot et al., 2014, 2017), although there is some indication of coherence on interannual and longer timescales (Frajka-Williams et al., 2018). Numerical modeling studies and inverse approaches have shown that the coherence of AMOC variability may be distinct between latitudes with coherent variability within the South Atlantic (Kelly et al., 2014, 2016), yet a lack of coherence between gyres in the North Atlantic (Bingham et al., 2007; Lozier et al., 2010) with slower propagation of anomalies in the subpolar regions (Zhang, 2007). AMOC observations will be required at a range of latitudes to reassess our expectations regarding meridional coherence between latitudes.

6.3.2. Boundary vs. Interior

Mesoscale activity results in high amplitude variability of ocean transports on subannual timescales (Wunsch, 2008), potentially introducing uncertainty in transport estimates when variations are not well-resolved in space or time. Mesoscale eddies are suppressed very near boundaries (Kanzow et al., 2009), however, reducing though not eliminating high frequency fluctuations for near-boundary measurements (Zantopp et al., 2017). Boundary currents, however, are more barotropic which, over sloping topography, limits the use of geostrophy to measure transports. As a consequence, AMOC observations require mesoscale-resolving sampling rates to calculate interior geostrophic transports, with absolute velocity observations over sloping topography.

6.3.3. Timescales

While the observed AMOC is variable on daily through decadal timescales, much of the interest in AMOC mechanisms and impacts is on seasonal and longer timescales. Forcing from wind and buoyancy show strong seasonal cycles, and potential impacts of AMOC changes may be relevant on seasonal timescales for e.g., improving seasonal forecasts of extreme summer European Temperatures (Duchez et al., 2016b). From 14 years of observations at RAPID 26°N, we have learned that the majority of the short term transport variability is driven by wind forcing, however the evolution of deep transport and watermass changes will be key to diagnosing buoyancy-forced variability with potentially lower frequency responses, anticipated in numerical adjoint analyses (Pillar et al., 2016).

6.3.4. Changes Not Yet Observed

AMOC transport and variability at 26°N is dominated by wind forcing on daily to interannual timescales, with the largest density variations in the top 1,000 m and on the western boundary (Zhao and Johns, 2014; Moat et al., 2016). However, on longer timescales and in a changing climate, buoyancy forcing at high latitudes and mixing in the abyssal ocean (Callies and Ferrari, 2018) or in the Southern Ocean within the Antarctic divergence (Toggweiler and Samuels, 1998) are expected to influence AMOC variations. These lower frequency variations are likely to appear as smaller amplitude temperature and salinity variations, at depth and potentially away from western boundaries. New observational methods, and testing of these strategies in models, may be required to improve accuracy of AMOC estimates, in order to link lower frequency drivers to the AMOC changes.

7. CONCLUSIONS AND OUTLOOK

This paper summarized observational efforts in the Atlantic to measure the continuously varying strength of the AMOC. From first transbasin measurements retrieved at 26°N by the RAPID array, a number of startling results have emerged (summarized in Srokosz and Bryden, 2015): that the AMOC ranged from 4 to 35 Sv over a single year, had a seasonal cycle with amplitude over 5 Sv, and that the dip in 2009/10 of 30% exceeded the range of interannual variability found in climate models. The international efforts to measure the AMOC in the Atlantic at a range of latitudes have delivered new understanding of AMOC variability, its structure and meridional coherence. *In situ* mooring arrays form the primary measurements of the large-scale meridional circulation, though the methodology used varies between latitudes and while some velocities and water mass properties are measured directly, there are also indirect inclusions of Ekman transport at the surface from reanalysis winds. These observations have informed and continue to inform numerical modeling efforts, which show striking differences between the AMOC mean state and variability amongst models (Danabasoglu et al., 2014, 2016). Due to the differences between simulations of the AMOC, and the importance of the AMOC in the climate system, sustained observations are needed to further advance mechanistic understanding of this large-scale circulation, and improve numerical models and climate simulations.

While the *in situ* arrays have demonstrated the value of high time resolution near boundary observations, the cost of these arrays is significant and still leaves gaps in AMOC observing (section 5). A range of observational techniques have been used to estimate the AMOC strength and variability both directly (from satellite and hydrographic data, section 3) and indirectly (through budgetary approaches or inverse methods, section 4). However, sparse sampling, particularly by the Argo float array, combined with the importance of boundary measurements to resolving transbasin transports, may mean that the uncertainties associated with these methods limit their utility in answering outstanding questions about AMOC mechanisms and impacts (section 6.1). In the future, while it is likely that a small number of observing arrays are necessary to maintain high quality, full time resolution estimates of the AMOC strength, significant gains can be made through monitoring efforts using distributed observations (satellite/Argo) or reduced costs of moored instrumentation with bottom pressure approaches (section 3.1). These approaches can reduce the costs of the AMOC-specific observations, while broadening the geographic coverage beyond individual latitudes. However, transitioning to new methods of sustained observing must be done with care to maintain the continuity of observations and data quality (Karl et al., 1996; National Research Council, 1999; World Meteorological Organization, 2008; Weatherhead et al., 2017). In particular, two recommendations made by Karl et al. (1996) and repeated many times subsequently are that

- Prior to implementing changes to existing systems or introducing new observing systems an assessment of the effects on long-term climate monitoring should be standard practice, and
- Overlapping measurements of both the old and new observing systems for *in-situ* and satellite data must become standard practice for critical climate variables.

These principles have been adopted in the development of the Global Tropical Moored Buoy Array (Freitag et al., 2018) and they apply equally well to observing systems for the AMOC. The problem with overlapping new and old measurement systems or instruments is that in the short-term there is an increased cost through operating both, though in the longer-term there may be significant savings. This approach, also known as parallel testing, should be the preferred approach (National Research Council, 1999; World Meteorological Organization, 2008).

While the observational records of the AMOC transport variability are relatively short, we have learned a great deal about the structure and variability of the AMOC volume, heat and freshwater transports, its response to wind forcing, and its meridional coherence (or lack thereof) between latitudes. As the records outside of the subtropical North Atlantic increase in length, intercomparisons between latitudes will permit understanding of the AMOC as a circulation system spanning gyres and hemispheres. New developments for observing carbon transports will illuminate the role of the AMOC in carbon storage in the deep ocean. As tools for comparing transports between observations and models are developed, we anticipate further gains in understanding of the AMOC mechanisms, drivers and impacts, and interactions between the ocean circulation and the atmosphere or cryosphere. These observing systems add considerable new knowledge to large-scale ocean circulation dynamics.

AUTHOR CONTRIBUTIONS

EF-W was the lead author. IJA, GD, SD, KAD, SE, RH, LCJ, JKa, ML, IAL, MSL, ELM, CSM, RCP, CGP, MR, MAS, and KET contributed to the writing. JB, HLB, MPC, SAC, GF, PH, NPH, HM, and BIM contributed to the editing. All authors including SB, GG, DK, JKo, TL, GDM, CM, US, DAS, SS, MvdB, DV and CW contributed to the analysis and to the revision of the manuscript.

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REFERENCES

Alexander-Turner, R., Ortega, P., and Robson, J. I. (2018). How robust are the surface temperature fingerprints of the Atlantic overturning meridional circulation on monthly time scales? *Geophys. Res. Lett.* 45, 3559–3567. doi: 10.1029/2017GL076759

Andres, M., Gawarkiewicz, G. G., and Toole, J. M. (2013). Interannual sea level variability in the western North Atlantic: regional forcing and remote response. *Geophys. Res. Lett.* 40, 5915–5919. doi: 10.1002/2013GL058013

Baehr, J. (2010). Influence of the 26°N RAPID-MOCHA array and Florida Current cable observations on the ECCO-GODAE state estimate. *J. Phys. Oceanogr.* 40, 865–879. doi: 10.1175/2009JPO4118.1

Baehr, J., Cunningham, S., Haak, H., Heimbach, P., Kanzow, T., and Marotzke, J. (2009). Observed and simulated estimates of the meridional overturning circulation at 26.5°N in the Atlantic. *Ocean Sci.* 5, 575–589. doi: 10.5194/os-5-575-2009

Baehr, J., Keller, K., and Marotzke, J. (2008). Detecting potential changes in the meridional overturning circulation at 26°N in the Atlantic. *Clim. Change* 91, 11–27. doi: 10.1007/s10584-006-9153-z

Balmaseda, M., Anderson, D., and Vidard, A. (2007). Impact of Argo on analyses of the global ocean. *Geophys. Res. Lett.* 34:L16605. doi: 10.1029/2007GL030452

Balmaseda, M., Hernandez, F., Storto, A., Palmer, M., Alves, O., Shi, L., et al. (2015). The ocean reanalyses intercomparison project (ORA-IP). *J. Operat. Oceanogr.* 8, s80–s97. doi: 10.1080/1755876X.2015.1022329

Bingham, R. J., and Hughes, C. W. (2008). Determining North Atlantic meridional transport variability from pressure on the western boundary: A model investigation. *J. Geophys. Res. Oceans* 112:C09008. doi: 10.1029/2007JC004679

Bingham, R. J., and Hughes, C. W. (2009). Signature of the Atlantic meridional overturning circulation in sea level along the east coast of North America. *Geophys. Res. Lett.* 36:L02603. doi: 10.1029/2008GL036215

Bingham, R. J., Hughes, C. W., Roussenov, V., and Williams, R. G. (2007). Meridional coherence of the North Atlantic meridional overturning circulation. *Geophys. Res. Lett.* 34:L23606. doi: 10.1029/2007GL031731

Boebel, O., Lutjeharms, J., Schmid, C., Zenk, W., Rossby, T., and Barron, C. (2003). The Cape Cauldron: a regime of turbulent inter-ocean exchange. *Deep-Sea Res. Pt. II* 50, 57–86. doi: 10.1016/S0967-0645(02)00379-X

Booth, B. B., Dunstone, N. J., Halloran, P. R., Andrews, T., and Bellouin, N. (2012). Aerosols implicated as a prime driver of twentieth-century North Atlantic climate variability. *Nature* 484, 228–232. doi: 10.1038/nature10946

Bower, A. S., Lozier, M. S., Gary, S. F., and Böning, C. W. (2009). Interior pathways of the North Atlantic meridional overturning circulation. *Nature* 459, 243–247. doi: 10.1038/nature07979

Bryden, H. L., and Imawaki, S. (2001). "Ocean heat transport," in *Ocean Circulation and Climate*, eds G. Siedler, J. Church, and J. Gould (New York, NY: Academic Press), 455–474

Bryden, H. L., Longworth, H. R., and Cunningham, S. A. (2005). Slowing of the Atlantic meridional overturning circulation at 25°N. *Nature* 438, 655–657. doi: 10.1038/nature04385

Buckley, M. W., and Marshall, J. (2016). Observations, inferences, and mechanisms of Atlantic meridional overturning circulation variability: a review. *Rev. Geophys.* 54, 5–63. doi: 10.1002/2015RG000493

Callies, J., and Ferrari, R. (2018). Dynamics of an abyssal circulation driven by bottom-intensified mixing on slopes. *J. Phys. Oceanogr.* 48, 1257–1282. doi: 10.1175/JPO-D-17-0125.1

Carrassi, A., Bocquet, M., Bertino, L., and Evensen, G. (2018). Data assimilation in the geosciences: an overview of methods, issues, and perspectives. *Wiley Interdiscip. Rev.* 9:e535. doi: 10.1002/wcc.535

Ceasar, L., Rahmstorf, S., Robinson, A., Feulner, G., and Saba, V. (2018). Observed fingerprint of a weakening Atlantic Ocean overturning circulation. *Nature* 556, 191–196. doi: 10.1038/s41586-018-0006-5

Clément, L., Frajka-Williams, E., Szuts, Z. B., and Cunningham, S. A. (2014). Vertical structure of eddies and Rossby waves and their effect on the Atlantic MOC at 26.5°N. *J. Geophys. Res.* 119, 6479–6498. doi: 10.1002/2014JC010146

Cunningham, S. A., Kanzow, T., Rayner, D., Baringer, M. O., Johns, W. E., Marotzke, J., et al. (2007). Temporal variability of the Atlantic meridional overturning circulation at 26.5°N. *Science* 317, 935–938. doi: 10.1126/science.1141304

Danabasoglu, G., Yeager, S. G., Bailey, D., Behrens, E., Bentsen, M., Bi, D., et al. (2014). North Atlantic simulations in Coordinated Ocean-ice Reference Experiments, phase II (CORE-II): Part I: mean states. *Ocean Model.* 73, 76–107. doi: 10.1016/j.ocemod.2013.10.005

Danabasoglu, G., Yeager, S. G., Kim, W. M., Behrens, E., Bentsen, M., Bi, D., et al. (2016). North Atlantic simulations in coordinated ocean-ice reference experiments phase II (CORE-II). Part II: inter-annual to decadal variability. *Ocean Model.* 96, 65–90. doi: 10.1016/j.ocemod.2015.11.007

de Ruijter, W. P. M., Biastoch, A., Drijfhout, S. S., Lutjeharms, J. R. E., Matano, R. P., Pichevin, T., et al. (1999). Indian-Atlantic interocean exchange: Dynamics, estimation and impact. *J. Geophys. Res. Oceans* 104, 20885–20910. doi: 10.1029/1998JC900099

Dijkstra, H. A. (2007). Characterization of the multiple equilibria regime in a global ocean model. *Tellus* 59A, 695–705. doi: 10.1111/j.1600-0870.2007.00267.x

Dong, S., Goni, G., and Bringas, F. (2015). Temporal variability of the South Atlantic meridional overturning circulation between 20°S and 35°S. *Geophys. Res. Lett.* 42, 7655–7662. doi: 10.1002/2015GL065603

Duchez, A., Courtois, P., Harris, E., Josey, S. A., Kanzow, T., Marsh, R., et al. (2016a). Potential for seasonal prediction of Atlantic sea surface temperatures using the RAPID array at 26°N. *Clim. Dynam.* 46, 3351–3370. doi: 10.1007/s00382-015-2918-1

Duchez, A., Frajka-Williams, E., Josey, S. A., Evans, D. G., Grist, J. P., Marsh, R., et al. (2016b). Drivers of exceptionally cold North Atlantic ocean temperatures and their link to the 2015 European heat wave. *Environ. Res. Lett.* 11:074004. doi: 10.1088/1748-9326/11/7/074004

Elipot, S., Frajka-Williams, E., Hughes, C., Olhede, S., and Lankhorst, M. (2017). Observed basin-scale response of the North Atlantic meridional overturning circulation to wind stress forcing. *J. Climate* 30, 2029–2054. doi: 10.1175/JCLI-D-16-0664.1

Elipot, S., Frajka-Williams, E., Hughes, C., and Willis, J. (2014). The observed North Atlantic MOC, its meridional coherence and ocean bottom pressure. *J. Phys. Oceanogr.* 44, 517–537. doi: 10.1175/JPO-D-13-026.1

Evans, D. G., Toole, J., Forget, G., Zika, J. D., Garabato, A. C. N., Nurser, A. J. G., et al. (2017). Recent wind-driven variability in Atlantic water mass distribution and meridional overturning circulation. *J. Phys. Oceanogr.* 47, 633–647. doi: 10.1175/JPO-D-16-0089.1

Forget, G., Campin, J.-M., Heimbach, P., Hill, C. N., Ponte, R. M., and Wunsch, C. (2015). ECCO version 4: an integrated framework for non-linear inverse modeling and global ocean state estimation. *Geosci. Model Dev.* 8, 3071–3104. doi: 10.5194/gmd-8-3071-2015

Frajka-Williams, E. (2015). Estimating the Atlantic MOC at 26°N using satellite altimetry and cable measurements. *Geophys. Res. Lett.* 42, 3458–3464. doi: 10.1002/2015GL063220

Frajka-Williams, E., Cunningham, S. A., Bryden, H. L., and King, B. A. (2011). Variability of Antarctic Bottom Water at 24.5°N in the Atlantic. *J. Geophys. Res.* 116:C11026. doi: 10.1029/2011JC007168

Frajka-Williams, E., Lankhorst, M., Koelling, J., and Send, U. (2018). Coherent circulation changes in the deep North Atlantic from 16°N and 26°N transport arrays. *J. Geophys. Res.* 123, 3427–3443. doi: 10.1029/2018JC013949

Freitag, H. P., McPhaden, M. J., and Connell, K. J. (2018). *Comparison of ATLAS and T-Flex Mooring Data*. Tech. Rep. OAR PMEL-149, NOAA/Pacific Marine Environmental Laboratory, Seattle, WA. doi: 10.25923/h4vn-a328

Goddard, P. B., Yin, J., Griffies, S. M., and Zhang, S. (2015). An extreme event of sea-level rise along the northeast coast of North America in 2009–2010. *Nat. Comm.* 6:6345. doi: 10.1038/ncomms7346

Haines, K., Valdivieso, M., Zuo, H., and Stepanov, V. N. (2012). Transports and budgets in a 1/4° global ocean reanalysis 1989–2010. *Ocean Sci.* 8, 333–334. doi: 10.5194/os-8-333-2012.002/qj.2063

Hela, I. (1952). The fluctuations of the Florida Current. *Bull. Mar. Sci. Gulf Carib.* 4, 241–248.

Hermanson, L., Dunstone, N., Haines, K., Robson, J., Smith, D., and Sutton, R. (2014). A novel transport assimilation method for the Atlantic meridional overturning circulation at 26°N. *Q. J. Royal Meteorol. Soc.* 140, 2563–2572. doi: 10.1002/qj.2321

Hughes, C. W., Elipot, S., Maqueda, M. M., and Loder, J. (2013). Test of a method for monitoring the geostrophic meridional overturning circulation using only boundary measurements. *J. Atmos. Ocean. Tech.* 30, 789–809. doi: 10.1175/JTECH-D-12-00149.1

Hughes, C. W., Williams, J., Blaker, A., Coward, A., and Stepanov, V. (2018). A window on the deep ocean: the special value of ocean bottom pressure for monitoring the large-scale, deep-ocean circulation. *Prog. Oceanogr.* 161, 19–46. doi: 10.1016/j.pocean.2018.01.011

Hummels, R., Brandt, P., Dengler, M., Fischer, J., Araujo, M., Veleda, D., et al. (2015). Interannual to decadal changes in the western boundary circulation in the Atlantic at 11°S. *Geophys. Res. Lett.* 42, 7615–7622. doi: 10.1002/2015GL065254

Iselin, C. O. (1940). Preliminary report on long-period variations in the transport of the Gulf Stream system. *Papers Phys. Oceanogr. Meteorol.* 8, 1–40.

Ivchenko, V. O., Sidorenko, D., Danilov, S., Losch, M., and Schröter, J. (2011). Can sea surface height be used to estimate oceanic transport variability? *Geophys. Res. Lett.* 38:L11601. doi: 10.1029/2011GL047387

Jackson, L. C., Peterson, K. A., Roberts, C. D., and Wood, R. A. (2016). Recent slowing of Atlantic overturning circulation as a recovery from earlier strengthening. *Nat. Geosci.* 9, 518–523. doi: 10.1038/NGEO2715

Johns, W. E., Baringer, M. O., Beal, L. M., Cunningham, S. A., Kanzow, T., Bryden, H. L., et al. (2011). Continuous, array-based estimates of Atlantic Ocean heat transport at 26.5°N. *J. Climate* 24, 2429–2449. doi: 10.1175/2010JCLI3997.1

Kanzow, T., Cunningham, S. A., Johns, W. E., Hirschi, J. J.-M., Marotzke, J., Baringer, M. O., et al. (2010). Seasonal variability of the Atlantic meridional overturning circulation at 26.5°N. *J. Climate* 23, 5678–5698. doi: 10.1175/2010JCLI3389.1

Kanzow, T., Johnson, H. L., Marshall, D. P., Cunningham, S. A., Hirschi, J. J.-M., Mujahid, A., et al. (2009). Basinwide integrated volume transports in an eddy-filled ocean. *J. Phys. Oceanogr.* 39, 3091–3110. doi: 10.1175/2009JPO4185.1

Karl, T. R., Knight, R. W., Easterling, D. R., and Quayle, R. G. (1996). Indices of climate change for the United States. *B. Am. Meteorol. Soc.* 77, 279–292. doi: 10.1175/1520-0477(1996)077<0279:IOCCFT>2.0.CO;2

Karspeck, A. R., Stammer, D., Kohl, A., Danabasoglu, G., Balmaseda, M., Smith, D. M., et al. (2017). Comparison of the Atlantic meridional overturning circulation between 1960 and 2007 in six ocean reanalysis products. *Clim. Dyn.* 49, 957–982. doi: 10.1007/s00382-015-2787-7

Kelly, K. A., Drushka, K., Thompson, L., Bars, D. L., and McDonagh, E. L. (2016). Impact of slowdown of Atlantic overturning circulation on heat and freshwater transports. *Geophys. Res. Lett.* 43, 7625–7631. doi: 10.1002/2016GL069789

Kelly, K. A., Thompson, L., and Lyman, J. (2014). The coherence and impact of meridional heat transport anomalies in the Atlantic Ocean inferred from observations. *J. Climate* 27, 1469–1487. doi: 10.1175/JCLI-D-12-00131.1

Kersalé, M., Lamont, T., Speich, S., Terre, T., Laxenaire, R., Roberts, M. J., et al. (2018). Moored observations of mesoscale features in the Cape Basin: characteristics and local impacts on water mass distributions. *Ocean Sci.* 14, 923–945. doi: 10.5194/os-14-923-2018

Köhl, A. (2015). Evaluation of the GECCO2 ocean synthesis: transports of volume, heat and freshwater in the Atlantic. *Q. J. Royal Meteorol. Soc.* 141, 166–181. doi: 10.1002/qj.2347

Kopp, R. E. (2013). Does the mid-Atlantic United States sea level acceleration hot spot reflect ocean dynamic variability? *Geophys. Res. Lett.* 40, 3981–4985. doi: 10.1002/grl.50781

Kuhlbrodt, T., Griesel, A., Montoya, M., Levermann, A., Hofmann, M., and Rahmstorf, S. (2007). On the driving processes of the Atlantic meridional overturning circulation. *Rev. Geophys.* 45:RG2001. doi: 10.1029/2004RG000166

Landerer, F. W., Wiese, D. N., Bentel, K., Boening, C., and Watkins, M. M. (2015). North Atlantic meridional overturning circulation variations from GRACE ocean bottom pressure anomalies. *Geophys. Res. Lett.* 42, 8114–8121. doi: 10.1002/2015GL065730

Le Bras, I. A., Yashayaev, I., and Toole, J. M. (2017). Tracking Labrador Sea Water property signals along the deep western boundary current. *J. Geophys. Res.* 122, 5348–5366. doi: 10.1002/2017JC012921

LeBel, D. A., Smethie, W. M. Jr., Rhein, M., Kieke, D., Fine, R. A., Bullister, J. L., et al. (2008). The formation rate of North Atlantic deep water and eighteen degree water calculated from CFC-11 inventories observed during WOCE. *Deep-Sea Res. Pt. I* 55, 891–910. doi: 10.1016/j.dsr.2008.03.009

Li, F., and Lozier, M. S. (2018). On the linkage between Labrador Sea Water volume and overturning circulation in the Labrador Sea: a case study on proxies. *J. Climate* 31, 5225–5241. doi: 10.1175/JCLI-D-17-0692.1

Li, F., Lozier, M. S., and Johns, W. (2017). Calculating the meridional volume, heat and freshwater transports from an observing system in the subpolar North Atlantic: observing system simulation experiment. *J. Atmos. Ocean. Tech.* 34, 1483–1500. doi: 10.1175/JTECH-D-16-0247.1

Little, C. M., Piecuch, C. G., and Ponte, R. M. (2017). On the relationship between the meridional overturning circulation, alongshore wind stress, and United States East Coast sea level in the Community Earth System Model Large Ensemble. *J. Geophys. Res.* 112, 4554–4568. doi: 10.1002/2017JC012713

Lopez, H., Dong, S., and Goni, G. (2017). A reconstructed South Atlantic meridional overturning circulation time series since 1870. *Geophys. Res. Lett.* 44, 3309–3318. doi: 10.1002/2017GL073227

Lozier, M., Gary, S., and Bower, A. (2013). Simulated pathways of the overflow waters in the North Atlantic: subpolar to subtropical export. *Deep Sea Res. Pt. II* 85, 147–153. doi: 10.1016/j.dsr2.2012.07.037

Lozier, M. S. (2012). Overturning in the North Atlantic. *Ann. Rev. Mar. Sci.* 4, 291–315. doi: 10.1146/annurev-marine-120710-100740

Lozier, M. S., Bacon, S., Bower, A. S., Cunningham, S. A., De Jong, M. F., De Steur, L., et al. (2017). Overturning in the subpolar North Atlantic program: a new international ocean observing system. *B. Am. Meteorol. Soc.* 98, 737–752. doi: 10.1175/BAMS-D-16-0057.1

Lozier, M. S., Li, F., Bacon, S., Bahr, F., Bower, A. S., Cunningham, S. A., et al. (2019). A sea change in our view of overturning in the subpolar North Atlantic. *Science* 363, 516–521. doi: 10.1126/science.aau6592

Lozier, M. S., Roussenov, V., Reed, M. S. C., and Williams, R. G. (2010). Opposing decadal changes for the North Atlantic meridional overturning circulation. *Nat. Geosci.* 3, 728–734. doi: 10.1038/ngeo947

Majumder, S., Schmid, C., and Halliwell, G. (2016). An observations and model-based analysis of meridional transports in the South Atlantic. *J. Geophys. Res.* 121, 5622–5638. doi: 10.1002/2016JC011693

McCarthy, G. D., Haigh, I. D., Hirschi, J. J., Grist, J. P., and Smeed, D. A. (2015a). Ocean impact on decadal Atlantic climate variability revealed by sea-level observations. *Nature* 521, 508–510. doi: 10.1038/nature14491

McCarthy, G. D., Smeed, D. A., Johns, W. E., Frajka-Williams, E., Moat, B. I., Rayner, D., et al. (2015b). Measuring the Atlantic meridional overturning circulation at 26°N. *Prog. Oceanogr.* 130, 91–111. doi: 10.1016/j.pocean.2014.10.006

McDonagh, E. L., King, B. A., Bryden, H. L., Courtois, P., Szuts, Z., Baringer, M., et al. (2015). Continuous estimate of Atlantic oceanic freshwater flux at 26.5°N. *J. Climate* 28, 8888–8906. doi: 10.1175/JCLI-D-14-00519.1

Meinen, C., Speich, S., Piola, A., Ansorge, I., Campos, E., Kersalé, M., et al. (2018). Meridional overturning circulation transport variability at 34.5°S during 2009–2017: baroclinic and barotropic flows and the dueling influence of the boundaries. *Geophys. Res. Lett.* 45, 4180–4188. doi: 10.1029/2018GL077408

Meinen, C. S., Garzoli, S. L., Perez, R. C., Campos, E., Piola, A. R., Chidichimo, M. P., et al. (2017). Characteristics and causes of Deep Western Boundary Current transport variability at 34.5°S during 2009–2014. *Ocean Sci.* 13, 175–194. doi: 10.5194/os-13-175-2017

Meinen, C. S., Johns, W. E., Garzoli, S. L., van Sebille, E., Rayner, D., Kanzow, T., et al. (2013). Variability of the deep western boundary current at 26.5°N during 2004–2009. *Deep Sea Res. Pt. II* 85, 154–168. doi: 10.1016/j.dsr2.2012.07.036

Mercier, H., L'herminier, P., Sarafanov, A., Gaillard, F., Daniault, N., Desbruyeres, D., et al. (2015). Variability of the meridional overturning circulation at the Greenland-Portugal OVIDE section from 1993 to 2010. *Prog. Oceanogr.* 132, 250–261. doi: 10.1016/j.pocean.2013.11.001

Mielke, C., Frajka-Williams, E., and Baehr, J. (2013). Observed and simulated variability of the AMOC at 26°N and 41°N. *Geophys. Res. Lett.* 40, 1159–1164. doi: 10.1002/grl.50233

Minobe, S., Terada, M., Qiu, B., and Schneider, N. (2017). Western boundary sea level: a theory, rule of thumb, and application to climate models. *J. Phys. Oceanogr.* 47, 957–977. doi: 10.1175/JPO-D-16-0144.1

Moat, B., Josey, S., Sinha, B., Blaker, A., Smeed, D., McCarthy, G., et al. (2016). Major variations in sub-tropical North Atlantic heat transport at short (5 day) timescales and their causes. *J. Geophys. Res. Oceans* 121, 3237–3249. doi: 10.1002/2016JC011660

Montgomery, R. B. (1941). Sea level difference between Key West and Miami, Florida. *J. Mar. Res.* 4, 32–37.

Munoz, E., Kirtman, B., and Weijer, W. (2011). Varied representation of the Atlantic meridional overturning across multidecadal ocean reanalyses. *Deep-Sea Res. Pt. II* 58, 1848–1857. doi: 10.1016/j.dsr2.2010.10.064

National Research Council (1999). *Adequacy of Climate Observing Systems*. Washington: DC: The National Academies Press.

Perez, F. F., Mercier, H., Vazquez-Rodriguez, M., L'herminier, P., Velo, A., Pardo, P., et al. (2013). Atlantic Ocean CO_2 uptake reduced by weakening of the meridional overturning circulation. *Nat. Geosci.* 6, 146–152. doi: 10.1038/ngeo1680

Piecuch, C. G., Bittermann, K., Kemp, A. C., Ponte, R. M., Little, C. M., Engelhart, S. E., et al. (2018). River-discharge effects on United States Atlantic and Gulf coast sea-level changes. *Proc. Natl. Acad. Sci. U.S.A.* 115, 7729–7734. doi: 10.1073/pnas.1805428115

Piecuch, C. G., and Ponte, R. M. (2015). Inverted barometer contributions to recent sea level changes along the northeast coast of North America. *Geophys. Res. Lett.* 42, 5918–5925. doi: 10.1002/2015GL064580

Pillar, H., Heimbach, P., Johnson, H., and Marshall, D. (2016). Dynamical attribution of recent variability in Atlantic overturning. *J. Climate* 29, 3339–3352. doi: 10.1175/JCLI-D-15-0727.1

Richardson, P. L. (2008). On the history of meridional overturning circulation schematic diagrams. *Prog. Oceanogr.* 76, 466–486. doi: 10.1016/j.pocean.2008.01.005

Roberts, C. D., Waters, J., Peterson, K. A., Palmer, M., McCarthy, G. D., Frajka-Williams, E., et al. (2013). Atmosphere drives observed interannual variability of the Atlantic meridional overturning circulation at 26.5°N. *Geophys. Res. Lett.* 40, 5164–5170. doi: 10.1002/grl.50930

Roessler, A., Rhein, M., Kieke, D., and Mertens, C. (2015). Long-term observations of North Atlantic Current transport at the gateway between western and eastern Atlantic. *J. Geophys. Res. Oceans* 120, 4003–4027. doi: 10.1002/2014JC010662

Sallenger, A. H. Jr., Doran, K. S., and Howd, P. A. (2012). Hotspot of accelerated sea-level rise on the Atlantic coast of North America. *Nat. Clim. Change* 2, 884–888. doi: 10.1038/nclimate1597

Schmid, C. (2014). Mean vertical and horizontal structure of the subtropical circulation in the South Atlantic from three-dimensional observed velocity fields. *Deep Sea Res. Pt. I* 91, 50–71. doi: 10.1016/j.dsr.2014.04.015

Send, U., Lankhorst, M., and Kanzow, T. (2011). Observation of decadal change in the Atlantic meridional overturning circulation using 10 years of continuous transport data. *Geophys. Res. Lett.* 38:24606. doi: 10.1029/2011GL049801

Smeed, D. A., Josey, S., Johns, W., Moat, B., Frajka-Williams, E., Rayner, D., et al. (2018). The North Atlantic Ocean is in a state of reduced overturning. *Geophys. Res. Lett.* 45, 1527–1533. doi: 10.1002/2017GL076350

Smeed, D. A., McCarthy, G., Cunningham, S. A., Frajka-Williams, E., Rayner, D., Johns, W. E., et al. (2014). Observed decline of the Atlantic meridional overturning circulation 2004 to 2012. *Ocean Sci.* 10, 29–38. doi: 10.5194/os-10-29-2014

Speich, S., Lutjeharms, J. R. E., Penven, P., and Blanke, B. (2006). The Indo-Atlantic exchange: dynamics of a regime transition from a western boundary current to an eastern boundary system. *Geophys. Res. Lett.* 33:L23611. doi: 10.1029/2006GL027157

Srokosz, M. A., and Bryden, H. L. (2015). Observing the Atlantic meridional overturning circulation yields a decade of inevitable surprises. *Science* 348:1255575. doi: 10.1126/science.1255575

Stammer, D., Balmaseda, M., Heimbach, P., Kohl, A., and Weaver, A. (2016). Ocean data assimilation in support of climate applications: status and perspectives. *Ann. Rev. Mar. Sci.* 8, 491–518. doi: 10.1146/annurev-marine-122414-034113

Stepanov, V. N., Haines, K., and Smith, G. C. (2012). Assimilation of RAPID array observations into an ocean model. *Q. J. Royal Meteorol. Soc.* 138, 2105–2117. doi: 10.1002/qj.1945

Takahashi, T., and Coauthors (2009). Climatological mean and decadal change in surface ocean pCO_2, and net sea-air CO_2 flux over the global oceans. *Deep Sea Res. Pt. II* 56, 554–577. doi: 10.1016/j.dsr2.2008.12.009

Tett, S. F. B., Sherwin, T. J., Shravat, A., and Browne, O. (2014). How much has the North Atlantic ocean overturning circulation changed in the last 50 years? *J. Clim.* 27, 6325–6342. doi: 10.1175/JCLI-D-12-00095.1

Thomas, C. M., and Haines, K. (2017). Using lagged covariances in data assimilation. *Tellus A* 69. doi: 10.1080/16000870.2017.1377589

Toggweiler, J. R., and Samuels, B. (1998). On the ocean's large-scale circulation near the limit of no vertical mixing. *J. Phys. Oceanogr.* 28, 1832–1852. doi: 10.1175/1520-0485(1998)028<1832:OTOSLS>2.0.CO;2

Toole, J. M., Andres, M., Bras, I. A. L., Joyce, T. M., and McCartney, M. S. (2017). Moored observations of the deep western boundary current in the NW Atlantic: 2004–2014. *J. Geophys. Res. Oceans* 122, 7488–7505. doi: 10.1002/2017JC012984

Trenberth, K. E., and Fasullo, J. T. (2017). Atlantic meridional heat transports computed from balancing Earth's energy locally. *Geophys. Res. Lett.* 44, 1919–1927. doi: 10.1002/2016GL072475

Trenberth, K. E., and Fasullo, J. T. (2018). Applications of an updated atmospheric energetics formulation. *J. Climate* 31, 6263–6279. doi: 10.1175/JCLI-D-17-0838.1

Weatherhead, E. C., Harder, J., Araujo-Pradere, E. A., Bodeker, G., English, J. M., Flynn, L. E., et al. (2017). How long do satellites need to overlap? Evaluation of climate data stability from overlapping satellite records. *Atmospher. Chem. Phys.* 17, 15069–15093. doi: 10.5194/acp-17-15069-2017

Williams, J., Hughes, C. W., and Tamisiea, M. (2015). Detecting trends in bottom pressure measured using a tall mooring and altimetry. *J. Geophys. Res. Oceans* 120, 5216–5232. doi: 10.1002/2015JC010955

Willis, J. K. (2010). Can *in situ* floats and satellite altimeters detect long-term changes in Atlantic ocean overturning? *Geophys. Res. Lett.* 37:L06602. doi: 10.1029/2010GL042372

Woodworth, P. L., Maqueda, M. A. M., Roussenov, V. M., Williams, R. G., and Hughes, C. W. (2014). Mean sea-level variability along the northeast American Atlantic coast and the roles of wind and the overturning circulation. *J. Geophys. Res. Oceans* 119, 8916–8935. doi: 10.1002/2014JC010520

World Meteorological Organization (2008). *WMO Statement on the Status of the Global Climate in 2007*. Tech. Rep. WMO- No. 1031, WMO, Geneva.

Wunsch, C. (2008). Mass and volume transport variability in an eddy-filled ocean. *Nat. Geosci.* 1, 165–168. doi: 10.1038/ngeo126

Wunsch, C., and Heimbach, P. (2006). Estimated decadal changes in the North Atlantic meridional overturning circulation and heat flux 1993–2004. *J. Phys. Oceanogr.* 36, 2012–2024. doi: 10.1175/JPO2957.1

Wunsch, C., and Heimbach, P. (2013). Two decades of the Atlantic meridional overturning circulation: anatomy, variations, extremes, prediction, and overcoming its limitations. *J. Climate* 26, 7167–7186. doi: 10.1175/JCLI-D-12-00478.1

Zanna, L., Heimbach, P., Moore, A., and Tziperman, E. (2011). Optimal excitation of interannual Atlantic meridional overturning circulation variability. *J. Climate* 24, 413–427. doi: 10.1175/2010JCLI3610.1

Zantopp, R., Fischer, J., Visbeck, M., and Karstensen, J. (2017). From interannual to decadal: 17 years of boundary current transports at the exit of the Labrador Sea. *J. Geophys. Res. Oceans* 122, 1724–1748. doi: 10.1002/2016JC012271

Zhang, R. (2007). Anticorrelated multidecadal variations between surface and subsurface tropical North Atlantic. *Geophys. Res. Lett.* 34:L12713. doi: 10.1029/2007GL030225

Zhang, R. (2008). Coherent surface-subsurface fingerprint of the Atlantic meridional overturning circulation. *Geophys. Res. Lett.* 35:L20705. doi: 10.1029/2008GL035463

Zhang, R., Delworth, T. L., Sutton, R., Hodson, D. L. R., Dixon, K. W., Held, I. M., et al. (2013). Have aerosols caused the observed Atlantic multidecadal variability? *J. Atmospher. Sci.* 70, 1135–1144. doi: 10.1175/JAS-D-12-0331.1

Zhang, R., Sutton, R., Danabasoglu, G., Delworth, T. L., Kim, W. M., Robson, J., et al. (2016). Comment on "The Atlantic Multidecadal Oscillation without a role for ocean circulation". *Science* 352, 1527–1527. doi: 10.1126/science.aaf1660

Zhao, J., and Johns, W. (2014). Wind-forced interannual variability of the Atlantic meridional overturning circulation at 26.5°N. *J. Geophys. Res. Oceans* 119, 2403–2419. doi: 10.1002/2013JC009407

Zou, S., Lozier, M. S., Zenk, W., Bower, A., and Johns, W. (2017). Observed and modeled pathways of the Iceland Scotland Overflow Water in the eastern North Atlantic. *Prog. Oceanogr.* 159, 211–222. doi: 10.1016/j.pocean.2017.10.003

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frontiers in Marine Science

REVIEW
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Successful Blue Economy Examples With an Emphasis on International Perspectives

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Careful definition and illustrative case studies are fundamental work in developing a Blue Economy. As blue research expands with the world increasingly understanding its importance, policy makers and research institutions worldwide concerned with ocean and coastal regions are demanding further and improved analysis of the Blue Economy. Particularly, in terms of the management connotation, data access, monitoring, and product development, countries are making decisions according to their own needs. As a consequence of this lack of consensus, further dialogue including this cases analysis of the blue economy is even more necessary. This paper consists of four chapters: (I) Understanding the concept of Blue Economy, (II) Defining Blue economy theoretical cases, (III) Introducing Blue economy application cases and (IV) Providing an outlook for the future. Chapters (II) and (III) summarizes all the case studies into nine aspects, each aiming to represent different aspects of the blue economy. This paper is a result of knowledge and experience collected from across the global ocean observing community, and is only made possible with encouragement, support and help of all members. Despite the blue economy being a relatively new concept, we have demonstrated our promising exploration in a number of areas. We put forward proposals for the development of the blue economy, including shouldering global responsibilities to protect marine ecological environment, strengthening international communication and sharing development achievements, and promoting the establishment of global blue partnerships. However, there is clearly much room for further development in terms of the scope and depth of our collective understanding and analysis.

Keywords: blue economy, macro-economic control policies, deep ocean stewardship, science-based products, data analysis and information delivery, ecological restoration

UNDERSTANDING OF BLUE ECONOMY

Since the 21st century, the concept of the "Blue Economy" has become increasingly popular. International society believes that blue economy covers three economic forms: economy coping with global water crisis[1] (McGlade et al., 2012); innovative development economy[2] (Pauli, 2009) and development of marine economy[3] (Behnam, 2012).

In the field of academic research, the research literature about blue economy mainly includes the following aspects. Kathijotes (2013) put forward the aim of Blue Economy models is to shift resources from scarcity to abundance, and to start tackling issues that cause environmental problems. Mulazzani et al. (2016) put forward the management tool based on ecosystem service framework to solve the coastal blue growth. Soma et al. (2018) proposed to achieve long-term sustainable blue growth through collaboration, inclusion and trust in the marine sector. van den Burg et al. (2019) focused on summarizing the possible boundaries of the growth of the marine industry from the spatial dimension of blue growth.

Most management research of the blue economy is based on a sustainable development perspective. Keen et al. (2018) designed a conceptual framework for blue economy can be used to assess sustainable marine management. Sarker et al. (2018) also developed a management framework of blue growth emphasizing that it requires joint efforts to promote blue growth and achieve sustainable development goals (SDGs). Howard (2018) had in-depth discussion on the role of stakeholders in sustainable development. The convergence of the blue economy and marine ecosystem, ecosystem accounting is closely linked to blue growth (Häyhä and Franzese, 2014; Lillebø et al., 2017).

Blue growth concept can be traced back to sustainable development, with the increase of international communication and in-depth study of the blue economy concept, more profound connotations are emerging. Interdisciplinary and multidisciplinary research is very important when studying blue economy cases, especially one of the main challenges is how to integrate across the involved disciplines.

Blue Economic Characteristics

Specifically, blue economy presents the following attributes:

Blue Economy Has a General Economy Attribute

Australia launched Blue Well-being Initiative, recognizing that ocean-based industrial development and growth, or blue GDP is of great potential to Australia's economic and social development (Commonwealth Scientific and Industrial Research Organisation [CSIRO], 2008). EU came up the concept of "blue growth" in 2012 (Committee of the regions, 2013). Therefore, many countries use "Blue Economy" as a policy tool or means to drive economic growth and create jobs. Focused on revitalizing economy, the marine industrial activities include construction, transportation, mineral resources development, ship building, communication cable laying, pharmaceutical enterprises, equipment deployment, sustainable energy from waves, currents, seaside leisure tourism, and fisheries and aquaculture. In addition to traditional marine development activities, marine oriented information and science sectors are playing an increasingly stronger role in boosting blue economy development.

Blue economy needs compliance with Sustainable Development Goal 14, with the attribute focused on conserve and sustainably use the oceans, seas and marine resources. The core is to realize social economic development and dynamic balance of resources and environment. In their second preparatory meeting summary, The United Nations Commission on Sustainable Development acting as Preparatory Committee highlighted approaches to adopt "blue economy," and believes it is consistent with the core contents of RIO+20 Summit (IOC/UNESCO et al., 2011). Green economy mentioned in Rio+20 negotiations represents a transformation of economic development model. International society tends to refer blue economy to green economy or green development model in ocean and coastal zone development and management (Rio+20 Pacific Preparatory Meeting, 2011). Based on analysis on marine industrial activities and the health of marine eco-system, we should maintain a healthy marine and land ecosystem, solve pollution such as marine transport waste and plastic litter and microplastic, mitigate the global change effects, and construct a blue economy sustainable management model based on maintaining a healthy ecosystem.

As "Blue" Signifies the Sea, Many Countries Consider the Blue Economy Refers to Marine Economy

United States Secretary of Commerce, addressed in 2012 Capitol Hill Ocean Week that United State's sea area actually has always been a strong economic engine. Some people refer it as "blue economy[4]". For example, Australia believes that the blue economy includes traditional and emerging marine industries and regards the value of marine industry as the value of the blue economy. India regards the blue economy as economic activities relying on the marine ecosystem or seabed. Blue development should increase the protection of adjacent waters, which means to enlarge blue economy space by expanding our development and protection to all marine (coastal and open ocean-deep sea) ecosystems. While alleviating pressures that reach the ocean originate in land and it is through atmospheric, riverine or connectivity that impacts reach the coastal ocean, we can further enhance our cognition toward the ocean.

Blue Economic Definition Overview

Blue Economy Is a Strategic Framework

Australia believes the essence of blue economy is to promote the development of marine industry which ecologically,

[1] Surface water and underground water are internationally defined as blue water. Rainwater that has not yet entered runoff is called green water, while gray water refers to discharged up-to-standard waste water.

[2] Blue economy business model is presented by Gunter Pauli. In The Blue Economy: A Report to the Club of Rome 2009, he defined blue economy as a sustainable business model by living in harmony with nature.

[3] Blue economy is a lifestyle that coexists with ocean, utilizes maritime resources and maintains a sustainable relation with ocean.

[4] Blue growth is defined as "smart, sustainable and exclusive economic and employment increase generated from ocean, ocean and coastal zone."

economically and socially benefit from marine ecosystem and ensure that the ecosystem-based management model should be the core in decision-making process of industrial and community development (Australian Government, 2012).

Blue Economy Is a Kind of Policy

In 2009, Maria Cantwell, United States Senator of Washington State, pointed out in the opening statement of the hearing on "The Blue Economy: The Role of the Oceans in our Nation's Economic Future" that "The "Blue Economy" – the jobs and economic opportunities that emerge from our oceans, Great Lakes, and coastal resources – is one of the main tools to rebuilding the United States economy."

Blue Economy Is a Part of Green Economy

UNEP and other international organizations extract blue economy from green economy. They encourages to tackle climate change via low-carbon and resource-efficient shipping, fishing, marine tourism, and marine renewable energy industries (UNEP et al., 2012).

Blue Economy Is a Sustainable Marine Economy

"We assume, "blue economy" is a sustainable marine economic development model. It is a new development mindset and its essence is to develop marine economy while protecting marine ecosystem well and finally achieving sustainable utilization of resources." Wang Hong said, Director of State Oceanic Administration under the Ministry of Natural Resources of the People's Republic of China, in China Marine Workshop of the United Nations Conference on Sustainable Development in 2012.

Blue Economy Is Marine-Based New Technology Economy

In its research report, Commonwealth Scientific and Industrial Research Organisation (CSIRO) of Australia mentioned "blue GDP," stressing that while developing diversified ocean-based industries, the idea of social and environmental sustainability has been implemented in the development under the support from new marine technologies and emerging industries (Commonwealth Scientific and Industrial Research Organisation [CSIRO], 2008).

Summary

In summary, Blue economy, as a macro economy concept, involves every aspect of national and global governance, economic development, environmental protection and sustainability and international communication. Blue economy is an integration of sustainable development and green growth. It highlights an overall-planning and coordinated development between marine ecosystem and ocean and coastal zone economic system. Considering the above features, we define the blue economy as sustainable productive, service and all other related activities using and protecting coastal and marine resources. There are many challenges in doing this which involve all sectors in the economy from private/industrial to research and development to NGOs to government policy. The complexity mentioned above offers both opportunities and barriers. The following sections address this from the perspective of selective use cases and experience moving forward. These perspectives are integrated near the end of the paper with approaches toward the balance of growth and ecosystem sustainability.

BLUE ECONOMY THEORETICAL CASES

This paper analysis the blue economy theories cases focus on three aspects: national macroeconomic management, policy framework and management technology.

National Macro-Economic Strategies

Since 2012, blue economy has entered the phase of practice and exploration. Some countries and regions have proposed strategic frameworks and action plans for developing the blue economy.

EU's Blue Growth Strategy and Blue Innovation Plan

In 2012, the European Union proposed the "Blue Growth" strategy, specifying that Blue Growth will be the core of marine policies and stating clearly key development areas and specific measures for the future. Blue Growth Strategy has launched initiatives in many policy areas related to Europe's oceans, seas and coasts, facilitating the cooperation between maritime business and public authorities across borders and sectors, and stakeholders to ensure the sustainability of the marine environment. In 2014, the Blue Economy Innovation Plan was launched, specifying that the plan will be executed from three aspects: (I) Develop sectors that have a high potential for sustainable jobs and growth, (II) Essential components to provide knowledge, legal certainty and security in the blue economy and (III) Sea basin strategies to ensure tailor-made measures and to foster cooperation between countries. In 2017, the EU issued the Report on the Blue Growth Strategy Toward More Sustainable Growth and Jobs in the Blue Economy, this report examines what has been learnt and what has been achieved since 2012, what is ongoing and what is still missing. Five aspects are described in the report: (I) pushing for growth in five focus areas, including blue energy, aquaculture, coastal and maritime tourism, blue biotechnology, sea bed mineral resources, (II) The benefits of marine data, spatial planning and maritime surveillance to facilitate growth in the blue economy, (III) promoting a partnership approach, (IV) boosting investment and (V) making blue growth strategy fit future challenge.

Indonesia's Sustainable and Equal Growth of Marine and Coastal Regions

Indonesia proposed the principles of developing marine and fishing industries based on their blue economy concept to: formulate comprehensive economy and environment protection policies; boost regional economic development; realize sustainable development by promoting clean production systems and encourage creative and innovative investment. The highlights of developing blue economy in Indonesia include: develop marine fishery, marine transportation, tourism, energy and material production industries based on the blue economy concept; further improve and coordinate marine and land economy national policies; develop blue economy demonstration zone; strengthen connections between trade and infrastructure and promote the development of technology and human resources. In addition, Indonesia also plans to set up blue economy demonstration zones in Lombok and Anamabs islands and Tomini bay, for exploring the blue economy model featured with marine industry, fishery, breeding, seaside tourism industries, small island collective, regional and bay development.

Blue Economy Development Policy Guidelines

Scientific Innovation of the Marine Industry

China has been pushing forward scientific innovations of the marine industry and has established six national marine economic innovation and development demonstration areas and sevennational industrial demonstration bases for rejuvenating marine industry with science and technology, of which several projects have achieved applaudable results, including Shandong Peninsula Blue Economic Zone, Blue Silicon Valley and the strategic cooperation among marine parks and bases in the Yangtze River Delta region.

Shandong peninsula blue economic zone

In 2011, The Shandong Peninsula Blue Economic Zone Development Plan was officially approved by the Chinese State of Council. It is China's first regional development strategy to focus on the marine economy (National Development and Reform Commission, 2011). The strategic positioning of Shandong Peninsula Blue Economic Zone is to develop into a modern marine industrial cluster with relatively strong international competitiveness, a world-leading education center of marine science, a pilot zone for national marine economic reform and opening up and a national key demonstration zone of marine ecological civilization. By 2015, Shandong Peninsula Blue Economic Zone has established a basic system of modern marine industry, significantly strengthened comprehensive economic strength, significantly improved the independent innovation capability of marine science and technology, prominently improved the quality of ocean and land ecological environment, constantly improved the landscape of the opening up of marine economy, and led other areas to achieve the general requirements of building a moderately prosperous society in all aspects. By 2020, Shandong Peninsula Blue Economic Zone will develop into a blue economic zone that features developed marine economy, optimized industrial structure, harmonious co-existence between human and nature and take the lead to fundamentally achieve modernization.

Blue silicon valley

On January 31, 2012, the work and management committees of Qingdao Blue Silicon Valley core area were officially established, marking the commencement of the overall planning and construction of Qingdao Blue Silicon Valley (Qingdao Municipal Government, 2012). Aiming to establish "China Qingdao Blue Silicon Valley, a new town of marine science and technology" and highlighting the functions of incubating scientific achievements and driving forward innovation, the project plans to build five new towns that deeply integrate scientific research, education and living. It also centrally plans key platform projects of marine science and research, education, achievement conversion and academic exchanges, speeds up the clustering of marine high-tech research and development, high-tech talents, high-tech industry and service organizations, significantly improves the abilities of independent innovation, achievement conversion and industry cultivation, endeavors to establish world-leading centers for marine scientific and technological research and development, centers for incubating and trading marine achievements, centers for cultivating emerging marine industries, centers for clustering blue education and talents, centers for blue tourism and healthcare, and becomes an innovation platform that enables China to scientifically develop and utilize marine resources and links global marine scientific research resources.

Strategic cooperation among marine parks and bases in the Yangtze river delta region

On June 8, 2018, several marine industrial parks and bases in the Yangtze River Delta region signed agreements to implement regional strategic cooperation. The strategic cooperation of marine industries in the Yangtze River Delta include five parks and bases in Nantong, Zhoushan, Shanghai Pudong, and Ningbo. The establishment of these parks and bases has two major foci: firstly, to elevate industrial cooperation, comprehensively manage industrial projects and resources to facilitate necessity-based selections, build service functions to guide project practices, promote orderly transfer and cluster development of marine industry within the region; secondly, to deepen cooperation between scientific innovation and talents, encourage colleges and institutions, scientific institutes and enterprises to establish cooperative research and development institutions and joint centers for technology transfer, achieve communications and integration in introducing marine talents, build joint mechanism for educating and cultivating talents and establish common criteria in recognizing talents (Chinese State of Council, 2014).

Widen Space for Blue Economy

Widening China's blue economy space

The 13th Five-Year Plan for Economic and Social Development of the People's Republic of China requires to widen space for the blue economy. In supporting industrial development, the Plan suggests to complement domestic fishery with distant water fishery to protect and maintain coastal fishery resources, restore marine ecological environment and effectively improve the on-going healthy development of distant water fishery. The Plan proposed several key maritime projects:

(1) Dragon in the deep-seas Achieve breakthroughs in key technological development of the Dragon Palace-I deep-sea experimental platform and construct deep-sea mobile and bottom-supported experimental platforms. Research and develop a system for integrated deep-sea environmental monitoring and activity exploration. Develop a shared platform for deep-sea equipment applications (China's search, 2018).

(2) Snow Dragon's Polar Exploration Establish a new shore-based observation station at Arctic Pole through cooperation, establish a new research station at Antarctic Pole, build new advanced icebreakers, improve Antarctic aviation capabilities, and complete the basic framework for land-sea-air observation platform in the polar regions (Science 24 hours, 2016). Research and develop exploration technology and equipment suitable to the polar environments, establish a service platform for the provision and application of information regarding the polar environments and potential polar resources.
(3) The multi-dimensional global ocean observation network Make overall planning for the layout of the national ocean observation (monitoring) network, move ahead with the development of real-time online monitoring systems and overseas observation (monitoring) stations for the marine environment, work toward establishing a multidimensional global ocean observation (monitoring) system, and strengthen observation and research of marine ecosystems, ocean currents, and maritime meteorology.

Blue economy in deep ocean stewardship initiative

A potential and topical sector for the promotion of the Blue Economy in our deep oceans is that of deep seabed mining for marine minerals and trace metals (Cuyvers et al., 2018; Lusty and Murton, 2018). The demand for minerals is increasing owing to reserves in land-based mines dwindling, as well as the potentially extensive environmental and social consequences of mining on land. Some suggest that land-based mining and recycling existing minerals alone may not fulfill the future demand for these resources (Hein et al., 2013). Minerals have potential for diverse industrial applications, including for green technologies, hence there is increasing attention to their extraction from the deep sea. Consequently, significant investments have already been made by some countries in terms of exploration for deep seabed mineral resources, developing sophisticated technology and conducting feasibility studies (for example the Japanese conducted their first test mining in 2017), and developing economic models under different commodity price scenarios and other geologic and financial considerations (Van Nijen et al., 2018; Volkmann et al., 2018). The exploitation of materials such as polymetallic sulfides, polymetallic nodules, cobalt-rich ferromanganese crusts (for nickel, copper, cobalt, zinc, manganese, gold, silver and other metals), as well as rare-earth elements, are of economic interest especially as these marine sources are often high-grade ores and therefore very valuable. Some of the main focus areas for this industry are the polymetallic nodules on the abyssal plain in the clarion-clipperton zone (CCZ) in the central Pacific Ocean, the seafloor massive sulfide deposits associated with hydrothermal vents in the Indian Ocean, and ferromanganese cobalt-rich crusts associated with seamounts in the West Pacific Ocean (Levin et al., 2016; Cuyvers et al., 2018).

Mining activities within national jurisdictions are governed locally but the extensive resources of those outside EEZs in The Area are under the jurisdiction of the International Seabed Authority (an intergovernmental body established by UNCLOS in 1982 to organize and regulate all mineral-related activities. Although deep-seabed mining may generate income for some nations, it will come at a high environmental cost with many unknown risks, some of which may become apparent only in the distant future (Levin et al., 2016; Gollner et al., 2017; Jones et al., 2018).

Deep-seabed mining comes with significant regulatory challenges (Bräger et al., 2018; Lodge and Verlaan, 2018). The environmental and social costs and future risks must be as fully understood as possible and be weighed against the short-term monetary gain (Voyer and van Leeuwen, 2019). In addition to obvious destruction of sea life living at the mine site, there are other adverse effects on biodiversity and ecological processes such as those associated with sediment-plume generation, toxic chemical release, noise, etc. (Levin et al., 2016; Vanreusel et al., 2016; Gollner et al., 2017; Jones et al., 2017; Tilot et al., 2018). The cumulative effects of these, along with other ocean pressures such as climate change (Guidetti and Danovaro, 2017) and pollution, need to be considered during this pre-mining phase in order to properly assess impacts. Integrated management of multiple economic sectors is a central tenet of blue growth and socially optimal use of ocean-based natural resources, but the mechanisms of implementation remain poorly understood (Klinger et al., 2018). Open access to environmental data is essential (Voyer et al., 2018) in order to achieve industry transparency and sound environmental management.

Deep-sea mining is, at the time of writing, rapidly approaching the commercial mining phase in multiple oceans, both in areas within and beyond national jurisdiction. There is an urgent need to identify and develop comprehensive, ecosystem-based management practices for deep-ocean environments subject to mineral extraction (Durden et al., 2017; Tunnicliffe et al., 2018). While overarching environmental objectives are needed, some practices will be resource and locality-specific. Transparent criteria for deep-sea institutional and corporate social responsibility also need to be established to respond to the challenges associated with sustainable use of resources (Ardron et al., 2018). Proactive development of environmentally considerate extractive technologies, practices, frameworks and policies prior to the onset of commercial mining (and taking into account the precautionary principle) will help to ensure effective stewardship and preservation of the marine environment, whilst enabling the use of seabed mineral resources (Durden et al., 2017).

While deep-seabed mining is discussed as a case study here, the deep ocean features in numerous other elements of the Blue Economy (Ramirez-Llodra et al., 2011; Mengerink et al., 2014). Deep-water fishing, which takes the form of bottom trawling, long lining, and now new mesopelagic fisheries are increasingly subject to ecosystem-based management (e.g., Grehan et al., 2017). The designation of protections (e.g., vulnerable marine ecosystems, marine protected areas, areas of particular environmental interest), the preparation of environmental impact assessments, stock assessment, fisheries regulations and other facets will all benefit from increased scientific input and stewardship approaches (Mengerink et al., 2014). Exploitation of gas hydrates or hydrothermal gradients as energy sources, of marine genetic resources for biopharmaceutical or industrial uses, and use of space for telecommunications cables are additional opportunities that would benefit as well. There is also a growing need for consciousness and regulation about carbon emissions and other climate impacts, debris, pollutants and contaminants introduced to the deep ocean associated with blue industries (Ramirez-Llodra et al., 2011).

Blue Economy Management Technology

Data Analysis and Information Delivery Support Observing Enterprises

The great lakes observing system (GLOS) is 1 of 11 Regional Associations in the integrated ocean observing system (IOOS). As certified regional information coordination entities, IOOS regions play a crucial role in coordinating their science and technology communities around the data and information priorities of resource managers and policy makers. In a geography as large as the Great Lakes, there are many academic, government and private entities that work in monitoring and science, and GLOS serves a role that is more focused on data management and aggregation services. Limited resources have also influenced the scope of GLOS' role in the region. Like other IOOS regions, GLOS provides direct resources to the sustained operations of local observing systems but in a more limited capacity. Similarly, GLOS has provided grants to partners for the development of models and information products or developed data tools and products directly, but typically as discrete projects that require further investment for sustained operations and maintenance.

The experience in the governance and management of GLOS provides a case study for why diversifying revenue is inherently important to sustaining observing and data management systems. Moreover, it has become critical for GLOS in a competitive market; one where organizations with similar names and broad missions can make it difficult to identify the best group for the job. GLOS is positioning itself to stay true to its mission while including non-traditional partners to achieve better results. The small size and 501c3 status of GLOS allows a less traditional approach to seeking partners and funding. GLOS addresses challenges in achieving its mission by applying creative funding and business models to areas of operations. Examples include (1) crowdsource funding to support the costs of ongoing operations and maintenance of observing assets; (2) multi-sector stakeholder agreements; and (3) service-based business models. While each of these examples has mixed success, they provide important insight about how the larger ocean observing enterprise might broaden its impact and grow the Blue Economy.

Crowdsource and private fundraising

As a function of its mission, GLOS provides financial support to an extensive network of over 35 nearshore buoys, gliders, and AUVs operating primarily in the nearshore areas of the Great Lakes, from Lake Superior to Lake Ontario.

An opportunity was presented when NOAA's Coastal Storms Program dedicated focus to the Great Lakes region and was looking to make smart investments in addressing critical information gaps related to coastal storms issues. Over the three-year period of working with the Coastal Storms Program[5], GLOS worked with the National Weather Service to support the capitalization of four new, privately operated, nearshore buoys placed in areas of critical importance for beach safety and shipping stakeholders. The agreements with the buoy operators was clear that funding would support the capitalization of the buoys but a financial plan (outside of federal grant funding) for sustained operations and maintenance of the buoys needed to be in place and supported by the operators.

Each of the four operators had unique stakeholder relationships that influenced their approach to finding sustainable operating funds. Two operators, the Regional Science Consortium (Erie, PA, United States) and Purdue University (Wilmette, IL, United States and Michigan City, IN, United States) have primarily absorbed ongoing operation costs by incorporating them into the regular outreach costs of affiliated education centers, the Tom Ridge Environmental Center and Illinois-Indiana Sea Grant, respectively. The other two operations, Northern Michigan University (Munising, MI, United States) and LimnoTech (Port Sheldon, MI, United States) relied more directly on donations from individual stakeholders.

In 2016, GLOS partnered with local buoy operator LimnoTech to demonstrate the viability of using private fundraising as a funding model to offset the annual buoy operations costs. The popular Port Sheldon buoy in Lake Michigan[6] that averaged 8,500 pageviews per week during the summer of 2018, is supported 100 percent by local contributions ranging from individuals to local fishing clubs, marinas, local government contributions, television news stations, and even a car dealership.

Though this appeared to be a successful model for local stakeholder engagement, emerging challenges cause concern that this type of fundraising is not a sustainable model for ongoing operations support. These experiences suggest that, while this might be a useful strategy for supplemental funding, it is not enough to serve as a sole funding source.

Multi-sector stakeholder agreements

As expensive buoys outlive their initial funding programs, GLOS is engaging public utilities to take on the ongoing expenses, leaving them with a high-quality observation instrument and GLOS with continued shared data and equipment utilization. The most successful demonstration of this is the service agreement between GLOS and the City of Cleveland, Ohio which involves a multi-sector partnership to support the operations of three buoys that provide critical water quality information for the city's drinking water system that serves over 1.5 million residents in the Cleveland area.

During the summer of 2006, over a twelve-day period, the City of Cleveland's water department was inundated with complaints from their customers about the taste, odor and color of the water. Areas of low oxygen and decomposing organic

[5]The Coastal Storms Program is a nationwide effort led by NOAA to increase mitigation efforts and reduce the risk associated with coastal storms. The program brings together a variety of federal, state and local organizations with the purpose of reducing loss of life and negative impacts on coastal property and the environment caused by coastal storms.

[6]http://glbuoys.glos.us/45029

matter, also known as hypoxia zones, were moving toward the city's water intakes. As Cleveland's information needs grew, NOAA's Great Lakes Environmental Research Lab and GLOS worked together to consider options for transitioning existing hypoxia research efforts at GLERL toward developing a more operational monitoring capacity for the city. Building from the process utilized with the Coastal Storms Program, GLOS used competitive grant funding to support the capitalization of an additional monitoring buoy to expand monitoring coverage in Lake Erie. Then in 2016, Cleveland Water entered into a service agreement with GLOS where Cleveland Water provides funds annually to GLOS to manage the annual buoy deployments, data collection and delivery.

The operations of the buoy are carried out by LimnoTech, a private engineering firm, with a portfolio of supporting science and engineering projects across the region, and in Lake Erie in particular. LimnoTech leverages the buoy operations work to support other clients including LEEDCo., a wind-energy development company that has also contracted with LimnoTech for the operations of another buoy in the area to assist with wind farm siting and planning. This multi-sector partnership serves as a model for GLOS in structuring other types of service-based agreements to support its data management and aggregation operations. Acknowledging the limitation of United States federal funding to support observations at regional and local level, it is important to consider the appropriate role and creative options for federal and local government, the private sector, and others to work together to meet important monitoring needs.

Data service based business models

As the management of GLOS has matured and evolved over time, it has become clear that data aggregation, integration, and service delivery are core to the organization's value proposition and are, arguably, a more appropriate function of its mission to prioritize resources toward given existing funding limitations at the Federal level. GLOS has several examples of partner agreements with both federal agencies and non-federal partners where data services, rather than direct support for observations, are the primary focus of the scope of work.

A recent example is the current Cooperative Agreement between GLOS and the United States Geographic Survey (USGS) to support improved coordination around various bathymetric and lake-bottom habitat mapping efforts in the region. Vast areas of the Great Lakes have not been mapped for bathymetry since the 1950s, leaving a major data gap that impedes progress in natural resource and habitat management. Contemporary mapping efforts are taking place with superior technology in a few constrained geographies, but largely in a piecemeal and uncoordinated fashion that limits benefits to multiple users. Multiple federal and state agencies, and academic institutions are engaged in bottom mapping activities as well as benthic biology in both the United States and Canada. These groups have begun to coordinate through the bottom mapping workgroup (BMW); an *ad hoc* group form with the goal of harmonizing collection, processing, and sharing of continuous high-resolution maps of Great Lakes bathymetry, sonar reflectance, bottom type classifications, and derived data products. While the BMW provides an effective regional coordinating mechanism, its progress has been hindered by the absence of dedicated capacity to coordinate meetings and outreach, create and manage web content, and carry out other activities. Although regional coordination on the issue of lake bottom mapping is increasing, essential pre-requisites to strategic investment in new data acquisition are missing.

Through the Cooperative Agreement with GLOS, USGS is committing resources to support a full-time employee to support coordination of data providers around the theme of bottom mapping, conduct a regional data inventory and needs assessment, draft lake floor mapping standards for the Great Lakes, and build the data infrastructure needed to discover, archive, and serve data to the public.

The USGS views GLOS as uniquely qualified to undertake this role. As the regional association for the Great Lakes within the United States integrated ocean observing system (IOOS) that is overseen by an inter-agency governing council, GLOS has a neutral posture that will allow them to work productively with a variety of agencies in the United States and Canada as well as non-federal partners including academic institutions and state agencies. GLOS is also able to leverage its existing infrastructure to support data assembly, quality control, discovery and access services for multiple data types and has a well-visited web service for data visualization and download.

This agreement serves as an example of how the role GLOS serves to the Great Lakes region is evolving with a greater emphasis toward that of a data assembly center (DAC) or regional information coordination entity (RICE). This is a good thing, as it is precisely the purpose and presumed benefit of the Certification process required through the Integrated Coastal and Ocean Observation System Act of 2009 (2009 ICOOS Act).[7] However, as this becomes a more viable area for growth, it undoubtedly has implications for the overall management and business model of the organization. These types of data services are growing in demand, and as GLOS builds its reputation and competencies as a certified regional information coordination entity, it can respond more often to requests for these services. GLOS is evolving its business model in this area where basic operations can be implemented as part of its mission, but cost recovery is required to grow and expand services.

Delimitation Technology for China's Marine Spatial Planning

Faced with the grim situation of tight resource constraints, serious environmental pollution, and degraded ecosystems, the Chinese government is taking the road of sustainable development. The concept of ecological civilization that respects nature, conforms to nature, and protects nature is established. In March 2018, China launched the largest reform of the State Council in the past 40 years, in which resources and environmental reforms were prominent. The Ministry of Natural

[7] In March of 2009, President Obama signed the Integrated Coastal and Ocean Observation System Act of 2009 (ICOOS Act). establishing statutory authority for the development of the United States integrated ocean observing system (IOOS). The ICOOS Act mandates the establishment of a national integrated system of ocean, coastal, and Great Lakes observing systems coordinated at the federal level.

Resources has been assembled, and performed the responsibilities of owning all natural resource asset, managing all territory utilization, protecting and rehabilitating ecological environment uniformly. The "two unification" responsibilities start a new era in natural resource management in China.

China is in a critical period transferring from high-speed development to high-quality development. The resource and environmental carrying capacity and the territory space development suitability are important scientific propositions which represent the interaction and coordinated development between man and nature. Since 2010, it has gradually become a basic work for central and local governments to determine regional strategies and policies, and make development planning. The resource and environmental carrying capacity refers to the comprehensive support levels of natural resource endowment conditions to human activities in a certain space, and is characterized by four aspects: resources, environment, ecology and disasters. We can evaluate the relative level of carrying capacity and identify the problems and risks of current utilization, thus promoting harmonious development of man and nature. The territory space development suitability is oriented to different development and utilization, considering spatial integrity and connectivity, location advantage, traffic convenience and other indicators, to judge the appropriateness of different development and utilization modes. It can provide scientific planning for development and utilization, and promote high quality development. At present, China has taken the assessment of resource and environmental carrying capacity and the territory space development suitability as the basis and premise of territory space planning. The dual evaluation and territory space planning at all levels will be launched soon, guiding scientific planning with resources and environment constrains, and leading green and high quality development with scientific planning (National Development and Reform Commission, 2017; China Research Intelligence Group, 2018).

Comprehensive Governance of Marine Environment

The Chinese Government attaches great importance to the prevention and control of marine environmental pollution. On November 30, 2018, the Ministry of Ecology and Environment, the National Development and Reform Commission and the Ministry of Natural Resources jointly issued the Action Plan for the Struggle of Comprehensive Governance of the Bohai Sea (Ministry of Ecology and Environment et al., 2018). The Action Plan clearly defined the overall requirements, scope and objectives, key tasks and safeguards for the comprehensive governance of the Bohai Sea, and put forward the timetable and roadmap for the Struggle of Comprehensive Governance of the Bohai Sea. The Action Plan proposes to improve the ecological environment quality of the Bohai Sea through comprehensive three-year management and solve the outstanding ecological and environmental problems in the Bohai Sea. By 2020, the proportion of the coastal waters in the Bohai Sea with good water quality (first and second water quality) will reach about 73%, the natural coastline retention rate will remain around 35%, the coastal wetland rehabilitation scale will not be less than 6900 hectares, and the coastline rehabilitation will increase by about 70 km.

The Action Plan calls for four key actions: land-based pollution control action, marine pollution control action, ecological protection and restoration action, and environmental risk prevention action. The land-based pollution control actions include: pollution control of rivers entering the sea; strict control of industrial pollution source discharge, completion of illegal and unreasonable clean-up of sewage outlets; promotion of agricultural, rural and urban pollution prevention and control; and reduction of land-based pollutants into the sea. The marine pollution control actions include: implementing marine aquaculture pollution control; implementing ship and port pollution control; carrying out comprehensive improvement of fishing port environment; marine garbage pollution prevention; and establishing a division of responsibilities and coordination mechanism for land and sea planning. The ecological protection and restoration actions include: ecological protection of coastal zones, delineation and strict observance of the red line of marine ecological protection in the Bohai Sea, comprehensive regulation and restoration of estuaries and bays, comprehensive management and restoration of coastal and shoreline, and conservation of marine living resources. Environmental risk prevention actions include: implementation of land-based emergency environmental incident risk prevention; implementation of marine oil spill risk prevention; marine ecological disaster warning and emergency response.

BLUE ECONOMY APPLICATION CASES

The blue economy application cases in this part mainly include two parts: One part is the science-based products and services that can underpin the development of the Blue Economy, seven AtlantOS use case examples were developed (**Figure 1**). The other part is China's marine integrated management based on ecological environment. This paper classifies all the cases into disaster prevention, pollution prevention, Marine industry support, system platform and ecological restoration.

Disaster Prevention

Assessing Harmful Algal Bloom Evolution in EU Atlantic Shelf Seas

Aquaculture is identified as a Blue Growth priority to ensure the sustainable supply of seafood to help meet increased food demands of the growing global population. Harmful Algal Blooms (HABs) are a recognized global problem with annual losses to aquaculture running into billions of Euros (Bernard et al., 2014). The AtlantOS HAB use case focuses on creating a weekly HAB bulletin for three European study areas in Norway, Ireland, and Spain. Experts who prepare the bulletins use the *in situ* ocean observing system, satellite data, and available numerical marine hydrodynamic modeling to provide a science-based product to indicate the current HAB status in areas of interest, accompanied by text describing the likely HAB occurrences in the days ahead (Cusack et al., 2018; example bulletins). Efforts in other parts of the world, the importance

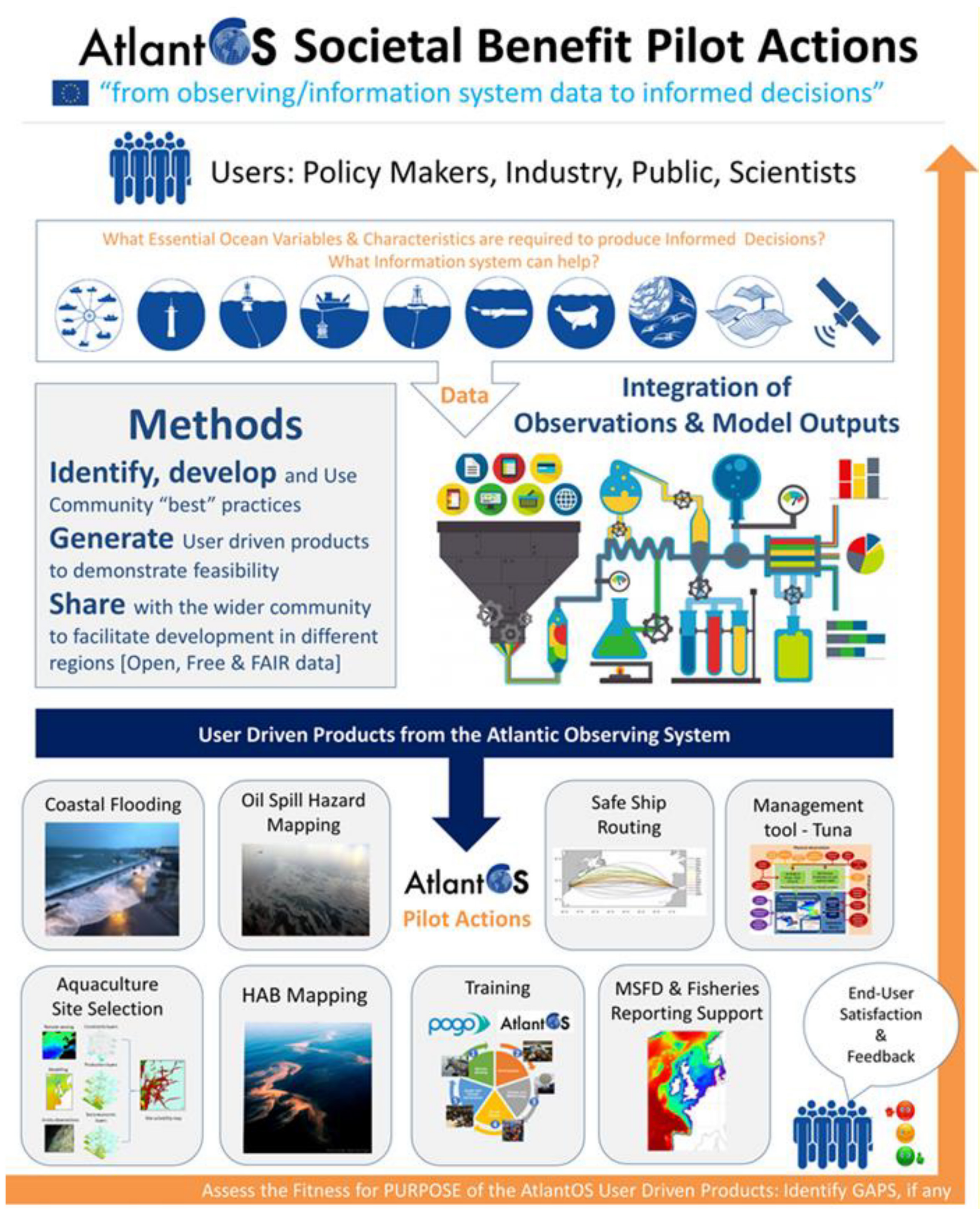

FIGURE 1 | AtlantOS societal databenefit pilot actions poster.

of co-development, and future expectations are discussed in Anderson et al. (see HABs white paper within this SI). In Europe, a key driver for HAB bulletins is to support industry on-site management decisions, such as optimizing farm practices and planning business activities to mitigate/reduce shellfish and finfish mortalities due to HABs.

Assessing and Mapping Ocean Hazards Related to Coastal Flooding and Storm Surges

Coastal flooding is one of the major challenges of global climate change for humanity. It is estimated that by 2070, approximately 150 million people and $35,000 billion of assets will be exposed to a 1 in 100 year flood event. Storm surges and oceanic waves are the major cause of extreme sea levels and devastating coastal impacts along many coastlines around the world with a significant human and economic cost. In order to improve our ability to assess the potential change of storm surge, it is critical to have a well-established baseline of the storm surge climate, based on consistent techniques. AtlantOS is laying the framework for a complementary international effort; developing a global storm surge climate has been adopted as a project under the IOC/WMO JCOMM Expert Team for Waves and Coastal Hazards. Statistical methods to both tide gauge data and multi-decadal runs of hydrodynamical numerical models are a "main" activity for the Sendai Framework of Disaster Risk Reduction. In this use case improvements were made to estimate extreme sea levels around the Atlantic and more widely with a new understanding gained about how storm surges and high tides interact, providing proof that any storm surge can occur on any tide (Williams et al., 2016). The sciences based products developed in this use case will help to enhance the safety of coastal communities by supporting the decision making process related to planning coastal defenses and emergency response to severe coastal flooding.

Pollution Governance

Mapping Ship Based Oil Spills to Estimate the Hazard That Maritime Transportation Represents to Atlantic Basin Coasts

The AtlantOS "oil spill hazard mapping and disaster risk reduction best practices" use case developed a large ensemble oil spill simulation experiment to guide oil spill risk assessments and emergency management. Risk maps can now be rapidly produced, within five minutes, to help evaluate an oil spill hazard (Neves et al., 2018). The hazard/risk mapping and production of oil spill hazard bulletins in the Atlantic are generated in an open access oil spill hazard map portal called glamor. In emergency situations, the users can map the oil spill hazard spatial distribution for any Atlantic coastal area based on the average oil spill concentration found at the coastline. The product provides a decision support tool to coastal managers and governments to help guide emergency clean-up operations and decisions on the allocation of resources to targeted high risk areas.

Overall Planning of Land and Sea to Strictly Control Pollutants

China appointing local government heads as river chiefs and bay chiefs across the nation to clean up and protect its water resources. Shandong proposed new pollution prevention idea of "governing river first, treating land and sea in a coordinated way." In Shandong, 15 rivers flowed into Laizhou Bay. In order to implement the responsibility of management and protection, Laizhou established a three-level "river chief" organization system of city, town and village. A total of 13 city-level "river chief," 44 town-level "river chief," and 662 village-level "river chief" were established. Since 2017, Laizhou has concentrated on the comprehensive management of Baisha River, Nanyang River and Zhenzhu River basins. A total of 42 million yuan has been invested, and about 25,000 meters of silt has been cleared up, more than 30 sewage outlets have been closed, and 64 polluted aquaculture households have been banned. After the linkage of the "river chief" and the "bay chief," the problem of repeated pollution in the Bay has been fundamentally solved (People's Daily, 2018).

Marine Micro Plastics: Impact and Governance

Microplastics are important component of marine litter, and also one of major global marine pollution problems (Arthur et al., 2009; Raubenheimer and McIlgorm, 2018). Microplastics are mainly caused by human activities (Cole et al., 2011). At present, microplastics have spread all over the world's major marine areas, and have had varying degrees of impacts on human development and the ecological environment, and some of the impacts are even devastating (Jambeck et al., 2015). Studies have found that microplastics have been found in biological cells, blood circulation systems and even the brains (Yu et al., 2018). In addition, a large number of plastics accumulate in estuaries and coasts, which will affect the marine ecological environment in coastal areas, and then affect the tourism industry, residents' lives and port terminals. Therefore, marine microplastics will adversely affect the sustainable utilization of blue economy.

The government is the coordinator of cooperative governance of microplastics. As the dominant government in the whole governance system, its functions include leadership, organization, coordination and supervision. Take China as an example, since 2007, China has actively carried out marine debris control work, and organized marine debris monitoring and evaluation in more than 50 representative areas along the coast. The monitoring area mainly includes areas with high public concern as well as sea areas where there is a large amount of potential marine debris and may affect the environmental quality of the sea area. The monitoring contents include types, quantities, weights and sources of beach garbage, floating garbage and submarine garbage. Since 2016, China has also implemented microplastic pilot monitoring, microplastics research and prevention research, polar and ocean micro-plastics investigation and monitoring. China also scientifically and strictly manages marine debris in accordance with relevant laws and regulations, technical standards and international conventions, and prevents solid waste such as plastic waste from affecting the marine ecological environment.

Since 2014, the United Nations has paid great attention to the pollution and control of microplastics. It has formulated a series of rules and taken relevant actions to strengthen the control of microplastics. For example, in February 2017, the United Nations Environment Program launched a global campaign calling on governments, industries and consumers to reduce the production and overuse of plastics. The campaign aims to eliminate the main sources of marine waste by 2022: plastic beads in cosmetics and overuse of disposable plastic products. In addition, resolutions of the United Nations Environment Congress on marine waste and microplastics (UnEA1 Resolution I/6 on marine waste and microplastics, UnEA2 Resolution II/11 on marine waste and microplastics, UnEA3 Resolution III/20 on marine waste and microplastics) provide partial solutions to the control of microplastics. The program emphasized the importance of global cooperative governance.

Enterprises are the micro-economic organizations for the cooperative governance of microplastics, as well as the main source of marine microplastics. Worldwide, especially in some developed countries, the sustainable use of packaging and plastics is regarded as part of corporate social responsibility (Vince and Hardesty, 2017). In 2011, the Global Declaration on Marine Waste Solutions issued by the Global Plastics Industry Association showed that 60 industry associations in 34 countries have signed the Declaration.

Marine Industrial Support

Developing an Aquaculture Site Selection Support Tool That Assesses Regional Oceanographic Conditions in Order to Identify Suitable Aquaculture Sites

Aquaculture is the fastest growing food production system in the world and a key ocean based economic activity sector expected to expand under the EU Blue Growth initiative. Such drivers, at local and global level, incentivize aquaculture to move offshore to the unprotected waters of the open ocean. Furthermore, appropriate site selection is needed to avoid competing demands for access and use of space, and prevent potential negative environmental impacts of the operations. In this AtlantOS use case, a GIS layered approach to identify potential offshore aquaculture sites was used. Ocean *in situ* and modeled GIS products were created and supported by data layers derived from satellites and/or administrative layers, e.g., coastline, infrastructure, fishing Areas, areas of conservation etc. (Dale et al., 2017). This initial pilot study showed that there is great potential for the use of GIS support tools to integrate information from *in situ* observations and model outputs over a hindcast period and then to couple this information with existing site decision tools and administrative layers, so potential aquaculture license applicants can pinpoint sites for further exploration to help the aquaculture sector develop in an environmental, economic and socially sustainable way.

Developing a Fisheries Management Tool for Atlantic Albacore Tuna

Progress in fish population modeling integrating environmental variables derived from Earth Observation and Operational Oceanography (COPERNICUS CMEMS program) has made it possible to create a demonstration of a near real-time forecast of one key tuna stock in the Atlantic Ocean. The AtlantOS use case developed a demonstrator for the albacore tuna to simulate in near real-time the change in abundance over time and space of this species by life stages i.e., larvae, juveniles, adults (Lehodey et al., 2017). The operational product is available on the seapodym model web site and is a great step toward improved real time monitoring of fishing activity and stock assessment that feed into the conservation measures, such as Total Allowable Catch, established by the International Commission for the Conservation of Atlantic Tunas.

Mapping CO2-Optimal Maritime Tracks, Based on Ocean State and Ocean Circulation

Regulatory decisions on ballast water treatment (2004), low Sulfur fuels (2008), and greenhouse gasses (2018) have been adopted by the International Maritime Organization (IMO) of the United Nations. In particular, the initial strategy for GHG reduction (MEPC.304(72), 2018) envisages a significant reduction of CO_2 emissions from ships before mid century, along with an increase in energy efficiency of maritime voyages. The latter can be achieved through technological, design, or operational measures. The contribution of the AtlantOS use case on ship routing is to provide maps of optimal ship tracks, which maximize the operational energy efficiency of the voyage (EEOI). Preliminary results for a North Atlantic passage indicate that the monthly average efficiency can be raised by up to about 10%, with a non-negligible contribution from the exploitation of the major ocean currents such as the Gulf Stream (Mannarini et al., 2018). In order to achieve these results, VISIR, an open source model for ship routing (Mannarini et al., 2016) was employed and further developed. The new modeling capabilities (including the source code) will be published soon. AtlantOS also plans to showcase VISIR results for low-carbon routes in the Atlantic through a dedicated web interface, providing a contribution to community efforts toward more sustainable navigation.

System Platform Services

Marine reanalyses enhance information collected from the *in situ* ocean observing system by assimilating observations into the North-west European Shelf Seas (NWS) numerical models, keeping the models close to reality, and providing a complete estimate of the evolving state of the ocean. The reanalyses (with *in situ* and remotely sensed observations) underlie the recent Copernicus Ocean State Report, providing an assessment the ocean state in the previous year. Understanding gained from reanalyses directly (through analysis of the reanalysis) and indirectly (i.e., via the Ocean State Report), can inform policy decisions relating to sustainable management of the NWS.

The use of NWS reanalyses, with global seasonal forecasting systems (such as the Met Office GloSea5 system), may extend NWS (temperature and salinity) predictability into the monthly-to-seasonal timescale, which would be of great benefit to European environmental and fisheries management (Tinker et al., 2018). Tinker et al. (2018) identified (and assessed) a number of pathways toward developing such a forecast, however, many challenges remain, and much research is required. Seasonal forecasts for the NWS would assist future operational management the NE Atlantic shelf seas and also has the potential to support marine operations sensitive to wind/wave conditions and currents such as the oil and gas industry, shipping, commercial and recreational fisheries.

Ecological Restoration

In the past 5 years, China has intensified efforts of wetlands treatment and restoration. With Blue Bay treatment projects, the ecological project to restore wetlands by developing mangrove forests in the south and Chinese tamarisk forests in the north, and the ecological island-reef restoration project, China has supported coastal regions to restore and recover coastal wetlands of 4,100 hectares, restore shorelines of more than 260 kilometers and restore beaches of more than 1,240 hectares. It is the goal to, by the end of 2020, treat and restore coastal wetlands of no less than 8,500 hectares (State Oceanic Administration of China, 2015), and establish a new batch of national, provincial, municipal and county level wetlands.

From 2016, China has been implementing the Blue Bay project to treat and restore marine ecosystem, which focuses on bays and expands to cover coastal regions and other damaged regions. In 2016, Panjin, Qinhuangdao, Shanwei, Xiamen and other cities, 8 in total, became the first batch of Blue Bay cities approved by the Ministry of Finance and the State Oceanic Administration

(Fang, 2016). Each city received central government subsidy of about RMB 300 million. Dalian, Qingdao and eight other cities were approved as the second batch Blue Bay cities in 2016. Each city received central government subsidy of about RMB 300 million. Moreover, according to implementation plans, the other part of supporting funds comes from local government financial funds and corporate/social funds, ranging from RMB 5 million to 4.5 billion. By the end of 2018, 18 Blue Bay projects are underway or near acceptance, with approximately 169 km of coastline, 2270 hm^2 of coastal wetlands, 11 islands and 38 km of beaches have been rehabilitated and restored. By 2020, Blue Action will focus on the governance of 18 bays suffering from serious pollution, push forward treatment and restoration of 50 small bays neighboring coastal cities, recover coastal wetlands of no less than 8,500 hectares, restore damaged near-shore seas of 4,000 square kilometers, treat and restore shorelines of 20 km. Most Blue Bay projects include some monitoring capacity building activities to monitor remediation effects, including observatory construction, on-line monitoring, drone monitoring, for water quality, hydrology and sea area utilization real-time data.

PROSPECT, PROPOSAL, AND DIRECTION

To understand, utilize and protect oceans are the shared goals and responsibilities for all human being to achieve sustainable marine development in the future. At present, blue economy, as the new development concept and the "blue engine," is becoming an important driving force for achieving global sustainable development. Environmental observations play a powerful technical supporting role in realizing blue economy development. Today, we focus on the development of blue economy, in a wish to, through joint efforts, push forward the accord development between blue economy and global economy, society and ecosystem in the next decade.

We should shoulder global responsibilities, step up deep-sea environmental management, understand the accumulative effects of human and climate on deep-sea creatures' diversity and ecological system's health, and strengthen controls targeting micro-plastics around global oceans, strive forward to establish a responsible community of marine ecological protection and marine environment governance, and push forward the establishment of a community of shared future that guarantees the sustainable development of oceans and human being.

We should share development achievements, let observing systems play a key role in verifying data, make data-driven decisions to affect blue economy sectors, strengthen international communications in terms of technology, human talents and information, and, by jointly designing and producing science-based products through collaborative public/private partnerships (Government, University, Enterprise, and Society), provide members with a platform to share policies, markets and growth.

We should push forward the establishment of blue partnerships around the globe, make mutual efforts to foster the new driving force of blue economy, explore new markets, generate new growth, co-establish service platforms and provide an industrial service platform of achieving global blue economy development, connecting technologies and markets, and also linking enterprises with finance.

AUTHOR CONTRIBUTIONS

LW and ZP: national macro-economic control policies, scientific innovation of the marine industry, red line of marine ecology. CC, AN, TD, KH, PL, GM, JT, EO, AR, SP, and JP (AtlantOS contribution): blue economy for science-based products, use case analysis of science-based products, developing, sharing and using ocean observing system "best practices" are essential for blue growth. MB, LL, EE, and DA: promotion of the blue economy in deep ocean stewardship initiative. CM and YaY: marine micro plastics, impact and governance. KP: data analysis and information delivery support observing enterprises. WT and YiY: cases of widening space for blue economy, treatment and restoration projects. ZX: ecological restoration.

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REFERENCES

Ardron, J. A., Ruhl, H. A., and Jones, D. O. B. (2018). Incorporating transparency into the governance of deep-seabed mining in the Area beyond national jurisdiction. *Mar. Policy* 89, 58–66. doi: 10.1016/j.marpol.2017.11.021

Arthur, C., Baker, J., and Bamford, H. (2009). *Proceedings of the International Research Workshop on the Occurrence, Effects and Fate of Microplastic Marine Debris*. Tacoma, WA: University of Washington Tacoma.

Australian Government (2012). *Australia's Submission to the Rio+20 Compilation Document, Rio+20 United Nations Conference on Sustainable Development*. Canberra: Australian Government.

Behnam, A. (2012). "Building a blue economy: strategy, opportunities and partnerships in the Seas of East Asia," in *The East Asian Seas Congress 2012*, Changwon.

Bernard, S., Kudela, R., and Velo-Suarez, L. (2014). "Chapter Eight: Developing global capabilities for the observation and prediction of harmful algal blooms," in *Oceans and Society Blue Planet*, eds S. Djavidnia, V. Cheung, M. Ott, and S. Seeyave (Newcastle upon Tyne: Cambridge Scholars Publishing), 46–53.

Bräger, S., Romero Rodriguez, G. Q., and Mulsow, S. (2018). The current status of environmental requirements for deep seabed mining issued by the International Seabed Authority. *Marine Policy* (in press). doi: 10.1016/j.marpol.2018.09.003

China Research Intelligence Group (2018). *The Assessment of Territory Space Development Suitability*. Available at: https://wenku.baidu.com/view/dd6b1e622379168884868762caaedd3382c4b57f.html (accessed September 11, 2018).

China's search (2018). *"Jiaolong" Explore the Sea: The World of the Deep Ocean is Beyond Your Imagination*. Available at: http://baijiahao.baidu.com/s?id=1600665570351702697&wfr=spider&for=pc (accessed May 17, 2018).

Chinese State of Council (2014). *Guiding Opinions on Relying on Golden Waterway to Promote the Development of Yangtze River Economic Zone*. Beijing: Chinese State of Council.

Cole, M., Lindeque, P., Halsband, C., and Galloway, T. S. (2011). Microplastics as contaminants in the marine environment: a review. *Mar. Pollut. Bull.* 62, 2588–2597. doi: 10.1016/j.marpolbul.2011.09.025

Committee of the regions (2013). *Blue Growth Opportunities for Marine and Maritime Sustainable Growth*. Brussels: Committee of the regions.

Commonwealth Scientific and Industrial Research Organisation [CSIRO] (2008). *Blue GDP: Ocean-Based Industrial Development and Growth*. Canberra: Commonwealth Scientific and Industrial Research Organisation.

Cusack, C., Silke, J., Ruiz-Villarreal, M., Eikrem, W., Dale, T., Moejes, F., et al. (2018). *Harmful Algal Bloom Bulletins. AtlantOS Deliverable, D8.6*. Kiel: AtlantOS, 36.

Cuyvers, L., Berry, W., Gjerde, K. M., Thiele, T., and Wilhem, C. (2018). *Deep Seabed Mining: A Rising Environmental Challenge*. Gland: IUCN.

Dale, T., Cusack, C., and Ruiz, M. (2017). *Aquaculture Site Selection Report. AtlantOS Deliverable, D8.2*. Kiel: AtlantOS, 39.

Durden, J. M., Murphy, K., Jaeckel, A., Van Dover, C. L., Christiansen, S., Gjerde, K., et al. (2017). A procedural framework for robust environmental management of deep-sea, mining projects using a conceptual model. *Mar. Policy* 84, 193–201. doi: 10.1016/j.marpol.2017.07.002

Fang, T. (2016). *Selected as One of the First Batch of Pilot Cities of "Blue Bay Regulation Action"*. Available at: http://qinhuangdao.jiwu.com/news/2587198.html (accessed August 18, 2016).

Gollner, S., Kaiser, S., Menzel, L., Jones, D. O., Brown, A., Mestre, N. C., et al. (2017). Resilience of benthic deep-sea fauna to mining activities. *Mar. Environ. Res.* 129, 76–101. doi: 10.1016/j.marenvres.2017.04.010

Grehan, A. J., Arnaud-Haond, S., D'Onghia, G., Savini, A., and Yesson, C. (2017). Towards ecosystem-based management and monitoring of the deep Mediterranean, North-East Atlantic and Beyond. *Deep Sea Res. II* 145, 1–7. doi: 10.1016/j.dsr2.2017.09.014

Guidetti, P., and Danovaro, R. (2017). Global ocean conservation under the magnifying glass. *Aquat. Conserv. Mar. Freshw. Ecosyst.* 28, 259–260. doi: 10.1002/aqc.2854

Häyhä, T., and Franzese, P. P. (2014). Ecosystem services assessment: a review under an ecological-economic and systems perspective. *Ecol. Modell.* 289, 124–132. doi: 10.1016/j.ecolmodel.2014.07.002

Hein, J. R., Mizell, K., and Barnard, P. L. (2013). Mineralogical compositions of sediment samples from the San Francisco Bay coastal system. *Pharmacopsychiatry* 46, 54–58. doi: 10.1594/PANGAEA.803903

Howard, B. C. (2018). Blue growth: stakeholder perspectives. *Mar. Policy* 87, 375–377. doi: 10.1016/j.marpol.2017.11.002

IOC/UNESCO, IMO, FAO, and UNDP. (2011). *A Blueprint for Ocean and Coastal Sustainability*. Paris: IOC/UNESCO.

Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., et al. (2015). Plastic waste inputs from land into the ocean. *Science* 347, 768–771. doi: 10.1126/science.1260352

Jones, D. O. B., Kaiser, S., Sweetman, A. K., Smith, C. R., Menot, L., Vink, A., et al. (2017). Biological responses to disturbance from simulated deep-sea polymetallic nodule mining. *PLoS One* 12:e0171750. doi: 10.1371/journal.pone.0171750

Jones, H. P., Jones, P. C., Barbier, E. B., Blackburn, R. C., Rey Benayas, J. M., Holl, K. D., et al. (2018). Restoration and repair of Earth's damaged ecosystems. *Proc. Biol. Soc.* 285:20172577.

Kathijotes, N. (2013). Keynote: blue economy - environmental and behavioural aspects towards sustainable coastal development. *Procedia Soc. Behav. Sci.* 101, 7–13. doi: 10.1016/j.sbspro.2013.07.173

Keen, M. R., Schwarz, A.-M., and Wini-Simeon, L. (2018). Towards defining the Blue Economy: practical lessons from pacific ocean governance. *Mar. Policy* 88, 333–341. doi: 10.1016/j.marpol.2017.03.002

Klinger, D., Eikeset, B., DavíЭsdóttir, A., Winter, M., and Watson, J. (2018). The mechanics of blue growth: management of oceanic natural resource use with multiple, interacting sectors. *Mar. Policy* 87, 356–362. doi: 10.1016/j.marpol.2017.09.025

Lehodey, P., Senina, I., Calmettes, B., and Titaud, O. (2017). *Operational Real-Time and Forecast Modelling of Atlantic Albacore Tuna. AtlantOS Deliverable*. Kiel: AtlantOS, 29.

Levin, L. A., Mengerink, K., Gjerde, K. M., Rowden, A. A., Van Dover, C. L., Clark, M. R., et al. (2016). Defining "Serious Harm" to the marine environment in the context of deep-seabed mining. *Mar. Policy* 74, 245–259. doi: 10.1016/j.marpol.2016.09.032

Lillebø, A. I., Pita, C., Garcia Rodrigues, J., Ramos, S., and Villasante, S. (2017). How can marine ecosystem services support the blue growth agenda? *Mar. Policy* 81, 132–142. doi: 10.1016/j.marpol.2017.03.008

Lodge, M. W., and Verlaan, P. A. (2018). Deep-sea mining: international regulatory challenges and responses. *Elements* 14, 331–336. doi: 10.2138/gselements.14.5.331

Lusty, P. A. J., and Murton, B. J. (2018). Deep-ocean mineral deposits: metal resources and windows into earth processes. *Elements* 14, 301–306. doi: 10.2138/gselements.14.5.301

Mannarini, G., Pinardi, N., and Coppini, G. (2018). "Low carbon intensity routes via ocean currents and waves," in *Technology and Science for the Ships of the Future, Proceedings of NAV 2018: 19th International Conference on Ship & Maritime Research*, eds A. Marinò and V. Bucci (Amsterdam: IOS Press BV), 340–347.

Mannarini, G., Pinardi, N., Coppini, G., Oddo, P., and Iafrati, A. (2016). VISIR-I: small vessels-least-time nautical routes using wave forecasts. *Geosci. Model Dev.* 9, 1597–1625. doi: 10.5194/gmd-9-1597-2016

McGlade, J., Werner, B., Young, M., Matlock, M., Jefferies, D., Sonnemann, G., et al. (2012). *Measuring Water Use in a Green Economy, A Report of the Working Group on Water Efficiency to the International Resource Panel*. Nairobi: UNEP.

Mengerink, K., Van Dover, C., Ardron, J., Baker, M., Escobar-Briones, E., Gjerde, K., et al. (2014). A call for deep-ocean stewardship. *Science* 344, 696–698. doi: 10.1126/science.1251458

Ministry of Ecology and Environment, The National Development and Reform Commission, and The Ministry of Natural Resources. (2018). *Action Plan for the Struggle of Comprehensive Governance of the Bohai Sea*. Beijing: Ministry of Ecology and Environment.

Mulazzani, L., Trevisi, R., Manrique, R., and Malorgio, G. (2016). Blue growth and the relationship between ecosystem services and human activities: the Salento artisanal fisheries case study. *Ocean Coast. Manag.* 134, 120–128. doi: 10.1016/j.ocecoaman.2016.09.019

National Development and Reform Commission (2011). *Development Planning of Blue Economic Zone in Shandong peninsula*. Beijing: National Development and Reform Commission.

National Development and Reform Commission (2017). *Some Opinions on Establishing a Long-term Mechanism for Monitoring and Early Warning of Resources and Environment Bearing Capacity*. Beijing: National Development and Reform Commission.

Neves, A. A. S., Pinardi, N., Martins, F., Janeiro, J., and Cesarini, C. (2018). *Oil Spill Hazard Bulletin*. Kiel: AtlantOS.

Pauli, G. (2009). *The Blue Economy——A Report to the Club of Rome*. Nairobi: UNEP.

People's Daily (2018). *Laizhou, shandong: Regulate the Pollution Into the Sea, and Take Care of the Bohai Sea*. Available at: http://sd.chinaso.com/sy/detail/20180825/1000200033118911535154219337365612_1.html. (accessed August 25, 2018).

Qingdao Municipal Government (2012). *Qingdao Blue Silicon Valley Planning*. Qingdao: Qingdao Municipal Government.

Ramirez-Llodra, E., Tyler, P. A., Baker, M. C., Bergstad, O. A., Clark, M. R., Escobar, E., et al. (2011). Man and the last great wilderness: human impact on the deep sea. *PLoS One* 6:e22588. doi: 10.1371/journal.pone.0022588

Raubenheimer, K., and McIlgorm, A. (2018). Can the basel and stockholm conventions provide a global framework to reduce the impact of marine plastic litter? *Mar. Policy* 96, 285–290. doi: 10.1016/j.marpol.2018.01.013

Rio+20 Pacific Preparatory Meeting (2011). *The "Blue Economy": A Pacific Small Island Developing States Perspective Apia, Samoa*. Apia: Rio+20 Pacific Preparatory Meeting.

Sarker, S., Bhuyan, M. A. H., and Rahman, M. M. (2018). From science to action: exploring the potentials of Blue Economy for enhancing economic sustainability in Bangladesh. *Ocean Coast. Manag.* 157, 180–192. doi: 10.1016/j.ocecoaman.2018.03.001

Science 24 hours (2016). *Snow Dragon's Polar Exploration*. Available at: https://www.cdstm.cn/gallery/media/mkjx/kx24xs/201705/t20170505_484413.html (accessed July 01, 2016).

Soma, K., van den Burg, S. W. K., Hoefnagel, E. W. J., Stuiver, M., and van der Heide, C. M. (2018). Social innovation – a future pathway for blue growth? *Mar. Policy* 87, 363–370. doi: 10.1016/j.marpol.2017.10.008

State Oceanic Administration of China (2015). *Implementing Scheme of Marine Ecological Civilization Construction (2015–2020)*. Beijing: State Oceanic Administration of China.

Tilot, V., Ormond, R., Moreno Navas, J., and Catalá, T. S. (2018). The benthic megafaunal assemblages of the CCZ (eastern pacific) and an approach to their management in the face of threatened anthropogenic impacts. *Front. Mar.* 5:7. doi: 10.3389/fmars.2018.00007

Tinker, J., Krijnen, J., Wood, R., Barciela, R., and Dye, S. R. (2018). What are the prospects for seasonal prediction of the marine environment of the Northwest European shelf? *Ocean Sci.* 14, 887–909. doi: 10.5194/os-14-887-2018

Tunnicliffe, V., Metaxas, A., Le, J., Ramirez-Llodra, E., and Levin, L. A. (2018). Strategic environmental goals and objectives: setting the basis for environmental regulation of deep seabed mining. *Mar. Policy* (in press). doi: 10.1016/j.marpol.2018.11.010

UNEP, FAO, IMO, UNDP, IUCN, World Fish Center, et al. (2012). *Green Economy in a Blue World*. Nairobi: UNEP.

van den Burg, S. W. K., Aguilar-Manjarrez, J., Jenness, J., and Torrie, M. (2019). Assessment of the geographical potential for co-use of marine space, based on operational boundaries for Blue Growth sectors. *Mar. Policy* 100, 43–57. doi: 10.1016/j.dib.2018.11.118

Van Nijen, K., Passela, S. V., and Squires, D. (2018). A stochastic techno-economic assessment of seabed mining of polymetallic nodules in the Clarion Clipperton Fracture Zone. *Mar. Policy* 95, 133–141. doi: 10.1016/j.marpol.2018.02.027

Vanreusel, A., Hiliario, A., Ribeiro, P. A., Menot, L., and Arbizu Martinez, P. (2016). Threatened by mining, polymetallic nodules are required to preserve abyssal epifauna. *Sci. Rep.* 6:26808. doi: 10.1038/srep26808

Vince, J., and Hardesty, B. D. (2017). Plastic pollution challenges in marine and coastal environments: from local to global governance. *Restor. Ecol.* 25, 123–128. doi: 10.1111/rec.12388

Volkmann, S. E., Kuhn, T., and Lehnen, F. (2018). A comprehensive approach for a techno-economic assessment of nodule mining in the deep sea. *Miner. Econ.* 31, 319–336. doi: 10.1007/s13563-018-0143-1

Voyer, M., Quirk, G., McIlgorm, A., and Azmi, K. (2018). Shades of blue: what do competing interpretations of the Blue Economy mean for oceans governance? *J. Environ. Policy Plann.* 20, 595–616. doi: 10.1080/1523908x.2018.1473153

Voyer, M., and van Leeuwen, J. (2019). 'Social license to operate' in the Blue Economy. *Resour. Policy* 62, 102–113. doi: 10.1016/j.resourpol.2019.02.020

Williams, J., Horsburgh, K. J., Williams, J. A., and Proctor, R. N. F. (2016). Tide and skew surge independence: new insights for flood risk. *Geophys. Res. Lett.* 43, 6410–6417. doi: 10.1002/2016gl069522

Yu, H., Liang, D., Tan, Q., and Li, J. (2018). Marine waste and microplastic pollution and its international process. *World Environ.* 2, 50–53.

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frontiers in Marine Science

REVIEW
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Meeting Regional, Coastal and Ocean User Needs With Tailored Data Products: A Stakeholder-Driven Process

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New coastal and ocean observing stations and instruments deployed across the globe are providing increasing amounts of meteorological, biological, and oceanographic data. While these developments are essential for the development of various data products to inform decision-making among coastal communities, more data does not automatically translate into more benefits to society. Rather, decision-makers and other potential end-users must be included in an ongoing stakeholder-driven process to determine what information to collect and how to best streamline access to information. We present a three-step approach to develop effective tailored data products: (1) tailor stakeholder engagement to identify specific user needs; (2) design and refine data products to meet specific requirements and styles of interaction; and (3) iterate engagement with users to ensure data products remain relevant. Any of the three steps could be implemented alone or with more emphasis than others, but in order to successfully address stakeholders' needs, they should be viewed as a continuum—as steps in a process to arrive at effective translation of coastal and ocean data to those who need it. Examples from the Regional Associations of the U.S. Integrated Ocean Observing System (IOOS®), the Texas General Land Office, and the Vanuatu Meteorology and Geo-hazards Department (VMGD) are woven throughout the discussion. These vignettes illustrate the value of this stakeholder-driven approach and provide a sample of the breadth of flexibility and customizability it affords. We hope this community white paper inspires others to evaluate how they connect their stakeholders to coastal and ocean observing data and provides managers of observing systems with a guide on how to evolve in a manner that addresses societal needs.

Keywords: coastal, ocean, observations, product development, stakeholder engagement, data products, stakeholder-driven

INTRODUCTION

Coastal communities have unique challenges and needs. Safe navigation, storm surge, shoreline run-up and erosion, extra-tropical systems, sea level rise, water quality, oil spills, marine debris, harmful algal blooms, and general ocean safety are concerns for those who live and work in close proximity to the ocean. Over the last decade, there has been an increase in the number of observing stations worldwide as part of the Global Ocean Observing System (GOOS) and other national and local programs (Liu et al., 2015; Willis, 2015), creating an opportunity to address the information needs of coastal communities. While this results in more data to monitor changing coastal and ocean conditions, more data does not automatically translate into more value for users. In other words, the data need to be accessible and in formats that are useful for end users. Indeed, many users need the data transformed to information that is clearly relevant to their professional or personal needs. Stakeholders differ in many ways, including level of ocean data knowledge and rate of data consumption (Iwamoto et al., 2016), cultural contexts, access to Internet and sufficient bandwidth, and more. Therefore, meeting user needs requires a tailored, iterative approach that connects users with data through value-added tools and data products that are both efficient and effective within their stakeholder context.

As a baseline, observing systems are typically a complex array of environmental sensors (e.g., physical oceanographic, meteorological, biogeochemical, biological) that are deployed from ships, integrated on buoys, moorings, platforms, autonomous vehicles, aircraft, and satellites. The data from these sensors help agencies (e.g., weather service agencies, tsunami warning agencies, public health agencies) to better understand our coastal and marine environments and provide data to their constituents. Further, people, including members of the public, may directly access these data for uses such as maritime operations, recreation, fishing, etc. These constituents, or stakeholders/users, are best defined as individuals, groups, or organizations who have an interest in a project or product, or who have a question or need that may be addressed by coastal and ocean data and information. These stakeholders can be within or outside the organization (Project Manager, 2019).

Based on over 142 years of accumulated experience in coastal ocean observing and working with stakeholders and users, we offer successful strategies to link society with coastal ocean data effectively. Herein, we promote the philosophy that well-designed observing systems address stakeholder-driven needs by design, explain why being stakeholder-driven is important, and describe a three-step process employed to develop products based on stakeholder needs.

The first step is to tailor stakeholder engagement to identify specific user needs. Unique cultures, environmental conditions, sectors, and politics, mean that a standard method (e.g., an electronic survey) to learn about a group's needs might not be sufficient to learn about or understand all groups' needs. Place-based, situational knowledge (i.e., the unique history, environment, culture, economy, politics, etc. of a particular community) all feed into how a particular stakeholder group views an issue, engages with partners, and expresses its needs (Bourne, 2016).

The second step is to design and refine data products to meet specific requirements and styles of interaction. There is a continuum of potential complexity among data products, and what works well for one audience might not work for another (e.g., a desktop data portal may work well for scientists needing to access many data layers at once, but is too complicated for a local fisher that needs to know if the ocean conditions are safe for a small boat on the other side of the island). Working iteratively with the users during the development process helps ensure optimal design.

The third step in this process is the exchange of knowledge for using the data. Understanding how a target audience uses a particular data product helps to ensure that the tool provides the intended utility, identifies where improvements might be necessary, and highlights the iterative nature of product development.

Overall, the creation of products and services is not "one size fits all." Unique geographies, differing levels of data management capability and Internet infrastructure, and regional or international differences in audiences require product development to be tailored to specific needs. Any of the three steps identified in this paper could be implemented alone, but in order to address stakeholders' needs most effectively, we strongly recommend viewing the approach as a continuum, as steps in a process to arrive at effective translation of coastal ocean data to those who need it. **Figure 1** illustrates the steps and components of this process, which are elaborated in the discussion below. Depending on the specific situation, certain approaches may have more emphasis than others. Examples woven throughout the discussion (**Table 1**) illustrate the value of this stakeholder-driven approach and the breadth of flexibility and customizability it affords.

This community white paper is offered as a resource in advance of the 2019 event for the decadal OceanObs conference series. The authors are committed to the notion that coastal and ocean observing systems need to benefit the stakeholders they serve and offer this paper as a guide to achieve this worthwhile mission. The steps delineated herein are based on the cumulative experience of the authors and ongoing community discussions. Examples from the Regional Associations of the U.S. Integrated Ocean Observing System (IOOS®), the Texas General Land Office, and the Vanuatu Meteorology and Geo-Hazards Department (VMGD) are provided. We hope to inspire others to evaluate how they connect their stakeholders to coastal and

Abbreviations: AOOS, Alaska Ocean Observing System; ASBS, Areas of Special Biological Significance; AUV, autonomous underwater vehicle; DSC, Data Standards Committee; GANDALF, Gulf Autonomous underwater vehicle Network and Data Archiving Long-term storage Facility; GCOOS, Gulf of Mexico Coastal Ocean Observing System; GOOS, Global Ocean Observing System; IOOS, Integrated Ocean Observing System; NANOOS, Northwest Association of Networked Ocean Observing Systems; NOAA, National Oceanic and Atmospheric Administration; NERACOOS, Northeastern Regional Association of Coastal Ocean Observing Systems; NWLON, National Water Level Observing Network; NWS, National Weather Service; PacIOOS, Pacific Islands Ocean Observing System; RMC, Resource Management Code; SCCOOS, Southern California Coastal and Ocean Observing System; SECOORA, Southeast Coastal and Ocean Regional Associated; SST, sea surface temperature; VMGD, Vanuatu Meteorology and Geo-Hazards Department.

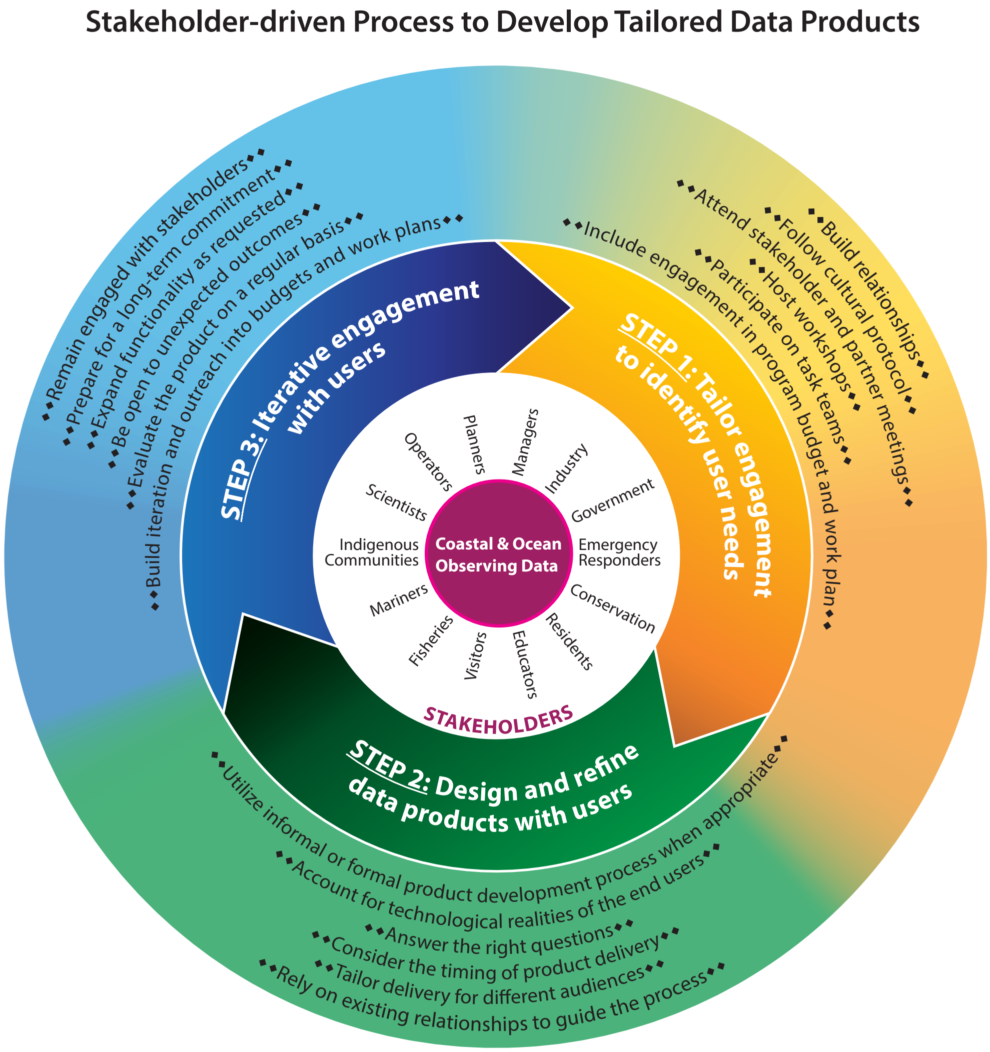

FIGURE 1 | This figure illustrates the stakeholder-driven process to develop tailored data products presented in this paper. The process starts in the center, with various stakeholders and their interactions and needs related to coastal and ocean observing data. Starting here is a reminder to first set the *intention* to operate a stakeholder-driven process. The three steps in the next rung of the image represent the three steps of this iterative, non-linear process—a continuum in which the three steps overlap and blend into each other as well as repeat. The outer rung includes the various elements or best practices to draw from when working through the various stages of this process.

ocean observing data and to provide managers of observing systems with a guide on how to evolve in a manner that addresses societal needs.

THREE STEPS TO A SUCCESSFUL STAKEHOLDER-DRIVEN PROCESS

Step 1: Tailor Engagement to Identify Specific User Needs

The first step in the stakeholder-driven process is to identify what people need. While this seems intuited and stakeholder needs may seem obvious, no one should assume that they inherently know the priorities or details of their users' needs. Programs must engage with their stakeholders in order to learn about the questions that need answered, the decisions that must be made, and the challenges to overcome. As stated by Worsley (2016, p. 16), "all projects will benefit from...stakeholder engagement, but the form of that engagement will vary with the nature of the project". Furthermore, unique cultures, environmental conditions, sectors, and politics, mean that the method to learning about one group's needs might not be sufficient to learn about or understand another group's. Indeed, the place-based, contextualized experiences of stakeholders play a significant role in how a particular stakeholder experiences and expresses a need (Bourne, 2016). This localized and contextualized background knowledge is vital, as are strong relationships built upon trust and mutual understanding.

TABLE 1 | List of organizations and web addresses for the data products described within this paper.

Organization	Acronym	Product name	More details
Alaska Ocean Observing System	AOOS	Alaska Water Level Watch	https://www.aoos.org/alaska-water-level-watch/
Gulf of Mexico Coastal Ocean Observing System	GCOOS	GANDALF	http://gandalf.gcoos.org/
Northwest Association of Networked Ocean Observing Systems	NANOOS	Shellfish Growers App	http://nvs.nanoos.org/ShellfishGrowers
Northeastern Regional Association of Coastal Ocean Observing Systems	NERACOOS	Ocean Climate Tool	http://neracoos.org/datatools/climatologies
Pacific Islands Ocean Observing System	PacIOOS	American Samoa SST email listserv	Simple daily email and tailored notification to interested stakeholders to accommodate for the territory's limited bandwidth.
Pacific Islands Ocean Observing System	PacIOOS	Hawaiʻi Sea Level Rise Viewer	http://www.pacioos.hawaii.edu/shoreline/slr-hawaii/
Southeast Coastal Ocean Observing Regional Association	SECOORA	How's the Beach	http://howsthebeach.org/
Southeast Coastal Ocean Observing Regional Association	SECOORA	Marine Weather Portal	http://mwp.secoora.org
Southern California Coastal and Ocean Observing System	SCCOOS	ASBS Explorer	http://www.sccoos.org/data/map/asbs.html
Texas General Land Office	GLO	Resource Management Code (RMC) web viewer	https://cgis.glo.texas.gov/rmc/index.html
Vanuatu Meteorology and Geo-hazards Department	VMGD	Vanuatu Ocean Outlook	See **Figure 6**

Structured, formal mechanisms of stakeholder engagement include hosting workshops and forums specific to areas of concern, participating on task teams, ratifying Memorandums of Agreement, and having a board of stakeholders that advise strategic directions. Even these efforts, though, are fostered first through informal relationship-building. For example, the U.S. IOOS Regional Associations are unlikely to sign contracts or Memoranda of Agreement without a foundation of trust and collaboration upon which they can base the agreement.

Build Relationships

Relationship-building can be fostered over time through both informal, unstructured (e.g., e-mails, meetings, conversations) and formal, structured (e.g., project management plans, presentations, contracts) mechanisms, although the informal often precedes the formal efforts (Mulcahy, 2013). Although communication technologies can help build bridges, face-to-face interactions are an important investment in relationships. In addition, some remote communities, such as in Alaska and in part of the Pacific Islands, have limited access to communication technologies (e.g., webinar, Skype) or the necessary bandwidth making that in-person connection even more necessary. In any of these contexts, listening, asking questions, and helping make connections all should occur before providing updates on one's own activities and capabilities. Examples of informal relationship building include participating in partner and community events and meetings, conducting site visits, and having one-on-one meetings.

Though essential, building relationships is not always easy. The geographic expanse of a particular observing system or organization, for example, can present a significant challenge to meaningful relationship-building. More remote locations require additional time and fiscal resources to be able to reach stakeholder communities, often either by plane or boat. In addition, the local cultures of some of these remote locations are also built upon oral traditions and are reliant on face-to-face personal interactions over a period of time to develop trust (Bishop and Glynn, 1992; Smith, 2004). This "showing face" can mean attending community events, following protocols, seeking out community elders—overall, becoming known to a community (Smith, 2004). Some common solutions employed across observing systems with very remote communities include supporting community-based liaisons, convening annual stakeholder meetings, and understanding that such efforts cannot be rushed. The timescale that these programs need to operate within is frequently much slower-paced than those in more connected (and typically developed) locations.

Vanuatu, for example, is a country with 83 islands, many of which are remote and difficult to access, requiring many days of travel to reach a particular village community. It can also be rather expensive to connect with these villages by small outboard motorboats. Telecommunications networks can be unreliable. However, Vanuatu has a hierarchical tier of engagement, from the national government to the grassroots level that is used to liaise with communities across the country. The national government offices work closely with the village chiefs accordingly through the local government or provincial council. The provincial council informs the area councils within the island, who then relay the message to the Community Disaster Committee & Community Climate Change Committee. These groups help communities to understand information that is made available for their use, and it is easy for the locals to convey their needs to these groups. Village meetings and church programs are also used to reach the community at large.

Through its Climate Services, the VMGD hosts the annual National Climate Outlook Forum to engage the community and specific sectors. This platform is used to share experiences and connections with the ocean and coasts. It is a way of engaging with community members at a grassroots level to learn about their needs and to work with them to determine how to best customize the department's products to suit stakeholder needs.

Many islands in the region of the Pacific Islands Ocean Observing System (PacIOOS) are also extremely remote and expensive for the Honolulu-based staff to visit in person. Like Vanuatu, many of the islands in the PacIOOS region are not accessible by plane and are only intermittently serviced by ships. In order to build a stronger connection with the community, PacIOOS supports partial salaries of on-site community liaisons that are either from the island they inhabit or are intimately integrated into the society, with long-term bonds and relationships. The liaisons are also well-versed in PacIOOS efforts and capabilities. Through these liaisons (in the Marshall Islands, Federated States of Micronesia, American Samoa, and Guam), PacIOOS can have face-to-face meetings, attend local community and agency meetings, and ultimately, build the trust that is so essential for successful engagement in the Pacific Islands. Once trust and mutual understanding are well-established, opportunities organically arise to showcase and highlight one's unique qualifications to help address stakeholder needs. The natural flow, then, is for communities to seek the observing system out to help achieve their respective missions and address their changing needs.

This was the case in American Samoa. After PacIOOS deployed a new wave buoy[1] in collaboration with the local maritime and ocean safety community, coral ecologists and natural resource managers reached out to the local PacIOOS liaison with a new need. It was apparent that it was going to be an El Niño year, and they were interested in using the data from the temperature sensor on the wave buoy (see footnote 1) to inform their field efforts to monitor coral bleaching. Moreover, they asked for a customized presentation of the data to meet their unique technological challenges and acute need. The established trust of the local liaison and by extension, the program, facilitated this request reaching PacIOOS in a timely manner. The resource managers work with the liaison frequently and were already familiar with the data management capabilities of the PacIOOS team. Therefore, they were confident that their request would be heard and addressed. Understanding the situation and need on the ground, the liaison advocated on behalf of the stakeholders. This example highlights how trust built overtime between an organization (i.e., PacIOOS) and the stakeholder community can lead to the users approaching the organization with their specific need.

Follow Cultural Protocol

One potential exception to employing informal means of building relationships before formal mechanisms is when engaging with indigenous communities. Such stakeholders often have formal structures and protocols in place to build relationships, garner input, and request permission and participation. This may entail local or regional indigenous governance bodies, councils of chiefs, village mayors, etc.

Sometimes informal cold calls can create frustration among groups that have this type of social infrastructure in place, which can inhibit trust-building and potentially derail a well-intended process. It is essential to follow the cultural protocols of a particular place. If the partners of a program do not know the protocols to follow, advice and counsel should be sought early in the process. Overall, sincere respect and a principle of reciprocity (i.e., equal exchange for mutual benefit) and feedback can go a long way toward building mutually beneficial partnerships (Smith, 2004) to ensure that the process and resulting data product truly meets the needs of stakeholders.

Attend Stakeholder and Partner Meetings

In other situations, it is possible to benefit from proximity and the efforts of other organizations or programs to gather their members at regularly scheduled meetings. A stakeholder need can surface through discussions, forums, and similar venues—either at one meeting or during successive meetings of a stakeholder group. Indeed, when participating in such meetings, members of an ocean observing system can both learn about the issues, questions, and needs that are being asked by that particular group and provide updates and inform the group of their capabilities.

Many ocean observing programs refer to this as "having a seat at the table" to learn about needs and opportunities. For example, staff members from the Northeastern Regional Association of Coastal Ocean Observing Systems (NERACOOS) regularly attend the state fisheries forums such as the Maine Fishermen's Forum and the Massachusetts Lobstermen's Annual Weekend and Tradeshow for these purposes. It was at such meetings that a common question kept surfacing among the fishermen and fisheries resource managers: "How do water temperature conditions in the Gulf of Maine this year compare with last year, previous years, or average conditions?" The overarching goal was for the fishermen and resource managers to better understand why their catch may have been different during the same months over the years. NERACOOS personnel realized they could help answer this question with data from their ocean sensors deployed on buoys offshore of New England. NERACOOS worked with the end users to develop requirements for the climatological data visualization tool that was launched in 2011[2].

The resulting tool (**Figure 2**) delivers information about the average meteorological and ocean conditions between 2001, and the most recent completed calendar year (currently 2018). The display also includes daily oceanographic and meteorological observations from each year so that users can compare them to the average conditions from the past 17 years. Fishermen, fisheries managers, fisheries scientists, and others have used this climate tool for over 7 years (Carla Guenther, personnel communication, November 13, 2017; Kathleen Reardon, personnel communication, July 17, 2018). These stakeholders regularly use the tool to monitor and investigate how present day ocean conditions compare to

[1] http://www.pacioos.hawaii.edu/water/buoy-aunuu/

[2] http://www.neracoos.org/datatools/climatologies

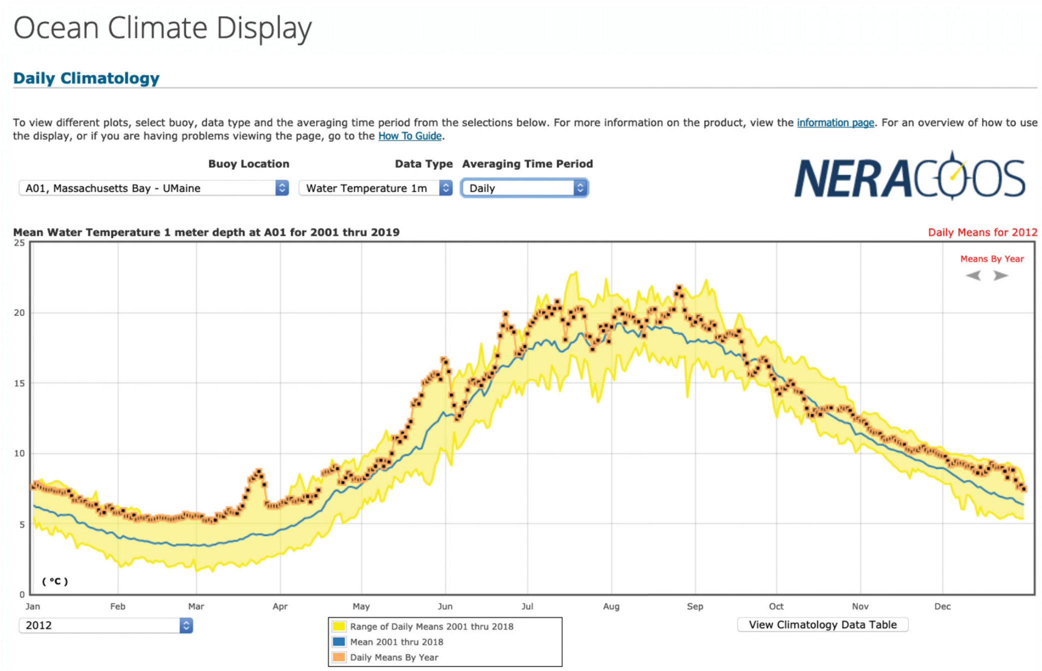

FIGURE 2 | The NERACOOS Ocean Climate Tool displays the daily average (blue line) and range (yellow area) of surface water temperatures at a buoy in the Gulf of Maine from 2001 to 2017. The 2012 daily mean water temperatures (black squares) demonstrate the "ocean heatwave" of 2012 when daily average surface water temperatures in the Gulf of Maine were consistently near or above the maximums measured in the previous decade. Image courtesy of NERACOOS.

historical and average conditions. In addition, this early success by NERACOOS inspired several other regional associations of U.S. IOOS to work with their interested stakeholders to develop similar climatology tools.

Host Workshops

Hosting successful workshops is another mechanism to elicit stakeholder needs, and one that requires a considerable amount of staff, stakeholder, and fiscal resources to plan, execute, and participate in the workshop. Logistics planning, reaching out to stakeholders, process planning, travel and workshop costs, and more must all be addressed in order to ensure that the workshop objectives are met. In addition, the workshop outcomes, such as workshop reports or next steps must be managed. But, there is also much to be gained in a workshop setting. Workshops provide a venue to learn about the opportunities or challenges of a specific topic, to be inclusive of particular communities or locales, to ensure that many voices are heard, to have the participants (as well as the sponsors) intermingle and learn more about each other, and to encourage synergistic ideas to surface.

In 2015, the Alaska Ocean Observing System (AOOS) hosted a coastal hazards workshop to identify priority data needs in response to increased coastal flooding, storm surge, and erosion across the region. This workshop provided a venue to bring together stakeholders from across Alaska to discuss priority regions needing water level information and potential alternatives to the National Oceanic and Atmospheric Administration (NOAA) Center for Operational Oceanographic Products' National Water Level Observing Network (NWLON) installations to deliver that information. In this way, local tribes and community members from remote Alaska, and especially in western and northern Alaska, were able to share their needs and learn about opportunities to work with AOOS and other partners to help fill their data gaps. NWLON technologies primarily consist of in-water sensors in stilling wells or down-looking microwave systems, and station siting is heavily reliant on ice-free conditions and local infrastructure, making annual operations and maintenance of a more widespread series of NWLONs cost prohibitive for most of the low infrastructure coastline in Alaska. Currently, the entire west and north coasts of Alaska have only five NWLON tide gauges. Though NWLON installations are always desirable for all water level data applications, a tiered water level data policy within NOAA allows for observations with lesser accuracies (Edwing, 2015). The policy stipulates water level data quality tiers A (e.g., NWLON, <10 cm), B (<30 cm), and C (>30 cm), matching data accuracy to specific applications. Tier B data can be used for hydrographic survey, shoreline mapping, marsh restoration, storm surge, exceedance, and inundation applications. Tier C data satisfy research and tsunami applications. To illustrate, tidal harmonic predictions and datums are easily derived from Tier B data; however, these outputs can only be used for Tier B applications and are not used in official NOAA National Ocean Service products. To this end, Tier B (and C) data satisfy a level of data accuracy that is necessary for many of the Alaska stakeholders' immediate safety and planning needs.

Since the workshop, AOOS and various partners across the region have implemented several resulting recommendations, including experimenting with and installing alternative water level technologies discussed in the report[3]. AOOS hosted a follow-up workshop in 2018 to bring together key water level technology experts, project leads, data end users, and other stakeholders to discuss progress made since 2016 and to develop a Water Level Build-out Plan for Alaska[4]. The plan (in review) will highlight priority water level observing gaps, as well as recommend which water level observing technologies are best suited for the specific water level application needs at each site within the scope of the tiered water level data policy. Another major outcome of this workshop was the establishment of the Alaska Water Level Watch (AWLW) working group. The group represents a full-range of stakeholder sectors, including federal, state, local municipality, communities, tribes, university, and industry members that are interested in improving the quality, coverage, and accessibility to water level observations in Alaska's coastal zone. This group meets annually, and is connected by the AWLW website hosted by AOOS[5], which also serves as a means for AOOS to receive outside input from all partners and users in need of water level information. The website will serve as a gateway to the AWLW Data Portal currently under development. The AWLW has a FaceBook page, and hosts individual community groups within the AWLW umbrella[6]. This allows communities to communicate internally on water level issues directly affecting them.

Participate on Task Teams

Another formal mechanism useful for certain situations or types of stakeholders is to participate on existing task teams or to build a new task team. This allows for the coordination among specific subsets of stakeholders to determine requirements and optimal options for addressing those requirements. Thanks to their manageable size, these teams can help streamline complicated processes and avoid frustration. The next two examples illustrate the various benefits of having formalized task teams in place.

Operators of ocean observing systems are comprised of experts in many related fields (e.g., physical oceanography, ocean chemistry, marine biology, etc.). As a result, they are often consulted as experts for specific questions or projects to address complex issues, such as the management of the Areas of Special Biological Significance (ASBS) designated by the California State Water Resources Control Board. As known experts in the field, and in the particular geography of interest, the Southern California Coastal and Ocean Observing System (SCCOOS) was asked to join a task team of partners to develop an online data explorer to manage urban runoff and protect the health of the two adjacent designated ASBS in La Jolla by ensuring compliance with the California Ocean Plan. Critical assessment questions that the partner coastal zone managers face include: (1) how to link trends and changes in the monitoring data to the management decisions made within the ASBS; and (2) whether the observed changes are a result of climate/natural variability, or if external, anthropogenic influences are impacting the ASBS. By joining this task team, SCCOOS was able to gain a comprehensive understanding of the partners' needs as well as contribute physical oceanography expertise and answer data management questions related to the online data explorer[7] as the project progressed.

In the Texas coastal zone, everything from surfing to oil and gas development occurs. The Texas General Land Office is charged with reducing conflicts among users and the natural environment while generating revenue and promoting economic development through the leasing of state submerged lands. Those seeking to lease submerged lands for activities, such as installing oil and gas infrastructure or dredging a private boat channel, needed a way to know what environmental sensitivities and restrictions may exist. In 2001, state and federal resource agencies developed a task team to address this need—resulting in what would be called the Resource Management Code (RMC) system. The RMC system assigns all state submerged lands tracts two-letter codes that alert potential users to possible restrictions of certain activities (e.g., dredging), the presence of sensitive environments and species, or conflicting activities in a specific tract. After the initial implementation of the system, this coordinated effort continues to bring together state and federal managers and experts who oversee different issues of the coast (from archeological resources to endangered species). The team framework facilitates collaboration between agencies with coastal management responsibilities and helps to identify common information needs. While users greatly benefit from the readily available information in the RMC, the task team and the associated RMC system help to protect natural resources and make the permitting process more efficient and transparent.

Include Engagement in Program Budget and Work Plan

Whether hosting a workshop or traveling to remote locations for face-to-face meetings to build relationships, tailoring engagement requires considerable resources, both financially and in terms of personnel time. Even those mechanisms that might be financially cheaper (e.g., attending partner and stakeholder meetings or coordinating task teams) still require staff resources to be successful. Therefore, no matter how an observing system tailors their stakeholder engagement, it is crucial to budget for the resources necessary. Simply, stakeholder engagement must be written into the program budget and annual work plans. The size of the budget and staff time necessary may vary greatly depending on the observing system (e.g., the geography of the region), the stakeholders (e.g., how they prefer to be engaged), the data (e.g., how often a new data layer is available or needs to be manually created), and the tool (e.g., maintenance, iteration).

Overall, once strong communication bonds and trust are established, both parties are invested in the process and the outcome. This makes it more likely that they will see a project through to the end (and beyond). The following sections continue with some of the examples introduced above to illustrate the next steps in the stakeholder-driven approach to data product development. Additional examples are also brought into the discussion to highlight specific aspects of the subsequent steps.

[3]http://aoos.org/wp-content/uploads/2011/05/2016_Alaska_Water_Level_Observations_v1-0.pdf

[4]https://aoos.org/alaska-water-level-watch/alaska-water-level-meeting-2018/

[5]https://www.aoos.org/alaska-water-level-watch/

[6]https://www.facebook.com/AlaskaWaterLevelWatch/

[7]http://sccoos.org/data/asbs/?p=20

Step 2: Design and Refine Data Products With Stakeholders for Specific End User Requirements and Styles of Interaction and Delivery

Successful data products are based on a comprehensive understanding of user needs. Sometimes a sophisticated data portal that allows for complex data integration across disciplines (e.g., oceanography, biology) is required, while at other times, stakeholders prefer a simple email alert system. Communication with stakeholders prior to and during the development of products helps project team members identify all of the relevant stakeholder communities, determine product requirements, and design products based on identified requirements and user limitations.

Utilize Informal Product Development When Appropriate

When the user community is small and has very specialized needs, iterative product development can happen informally. For example, the Gulf of Mexico Coastal Ocean Observing System (GCOOS) developed the tool Gulf Autonomous underwater vehicle Network and Data Archiving Long-term storage Facility (GANDALF), the Gulf autonomous underwater vehicle (AUV) Network and Data Archiving Long-term storage Facility[8], specifically for their AUV (**Figure 3**) operators. The tool (**Figure 4**) assists AUV pilots operating in the Gulf of Mexico by providing real-time vehicle positioning information via a map-based interface. Users have access to a dashboard display, plots of flight and science sensors, Google Earth KMZ file generation, and processed data files. GANDALF is equipped with numerous data layers that can be individually displayed on the base map. The layers were added per individual requests from different glider pilots. Each layer's transparency can be individually adjusted allowing for 'mash-ups' of layers. Provided layers include NWS NEXRAD (radar), GOES visible and GOES infrared satellite images, sea surface temperature (SST) and chlorophyll images from the University of South Florida, sea surface heights from the Colorado Center for Astrodynamics Research, and NOAA raster navigational charts. In addition to the observational layers, several model outputs are available on GANDALF, such as the Office of Naval Research's ensemble of sea surface velocity, SST, and sea surface elevation. Operators of AUVs find these parameters helpful in navigational planning, as surface wave action, subsurface currents and temperature changes heavily influence the flight path.

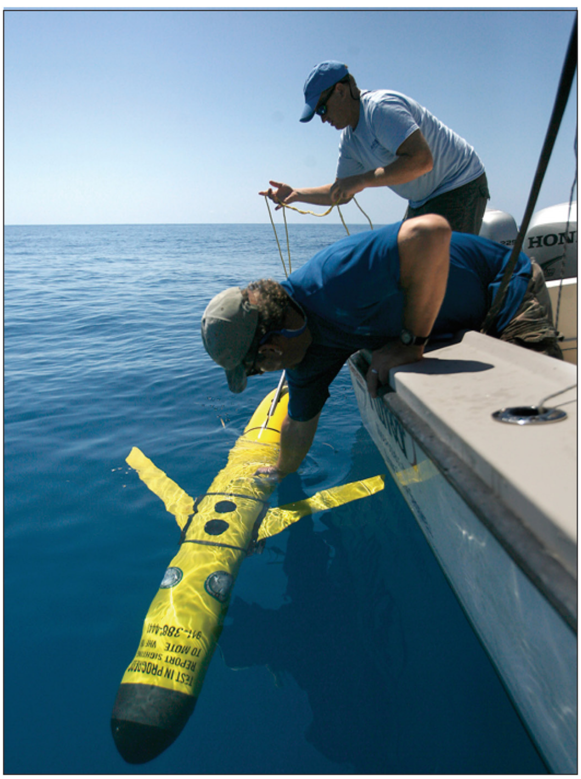

FIGURE 3 | Mote Marine Laboratory scientists deploy a Slocum glider, an autonomous underwater vehicle (AUV), for harmful algal bloom research on the West Florida Shelf. Photo courtesy of Mote Marine Lab.

During a glider deployment, NetCDF[9] files are created from uploaded glider data files and uploaded to a federal data repository, specifically the NOAA IOOS Glider Data Assembly Center, where others can access the data. GANDALF also provides post-processing of mission data for AUV operators. Binary data files and text log files are downloaded from operators' servers, and publication quality plots are generated. Mission files are permanently archived on the GANDALF server. GANDALF provides valuable services for AUV operators and is particularly useful to operators who have little or no IT support.

The resulting data platform is a collaborative product that is enhanced on an as-needed basis, as glider operators identify a new layer or functionality that they would like included. GANDALF services are provided at no cost to users: all that is needed is access to glider data files. This product has been so well received from the glider operators that GCOOS has extended the use of the tool to the Southeast Coastal Ocean Observing Regional Association (SECOORA). As further testament to its success, Jordon Beckler from Florida Atlantic University/Harbor Branch Oceanographic Institute states:

GANDALF has absolutely revolutionized our glider deployments, from preparation, to piloting, to recovery...Beyond just the drastically increased efficiency, however, GANDALF also provided ancillary data useful for decision making during piloting. We were attempting to locate harmful algal blooms based on elevated chlorophyll signatures, and the contour plots really allowed us to discern subtle patterns, while the chlorophyll surface maps allowed us to compare what was happening at depth to the surface. The detailed NOAA bathymetry charts are critical when flying gliders in shallow water regions when chasing a harmful algae bloom toward shore and wondering if your

[8] http://gandalf.gcoos.org

[9] NetCDF files are a common data format used for storing, retrieving, and sharing data (NetCDF 4.6.2, 2019).

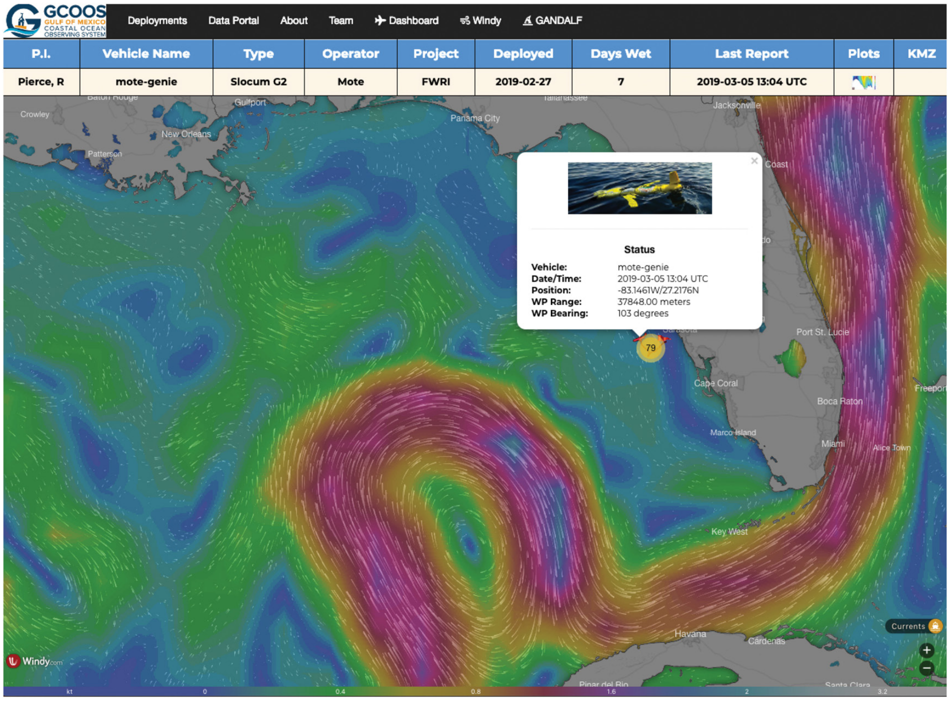

FIGURE 4 | GANDALF AUV piloting portal showing deployed vehicles and waypoints. Vehicles that have recently reported their positions are shown as green, vehicles that have not reported in 48 h are shown in red. Lack of communication can be caused by many factors but is typically a sign of rough seas and bad weather conditions. Image courtesy of GCOOS.

glider is going to crash into the seafloor. Finally, the...seawater velocity overlays are really useful in understanding glider drift from in a synoptic sense, which is both useful for pinpointing algae bloom dynamics, but also in careful flying to ensure you will not drift into shipping lanes – which I may add, are also [available] on GANDALF!

Employ a Formal Product Development Process When Appropriate

In other cases, such as the NERACOOS climatology tool mentioned in Step 1 (see Section "Attend Stakeholder and Partner Meetings"), it is advantageous to set up a formal product development process. Since a wide range of users needed the product, NERACOOS' product team developed and implemented an end-to-end product development process. The first phase of the process included a review of current relevant climatological products. The team then conducted a survey among potential end users to better understand their information needs and how they preferred to view and access that information. A subset of the potential end users were interviewed to help refine the product requirements. Using information from the review, survey, and interviews, a suite of functional and technical requirements were developed. The product developers and designers created a draft product that was tested by potential users. Feedback from the testing informed updates to the product. The product team also worked with an expert group to develop and test the process for climatology calculations. After a series of testing and refinement cycles, the product was officially launched on the NERACOOS website. The launch included a marketing campaign aimed at key stakeholders including commercial fishermen, fisheries managers, and fisheries scientists. The campaign included social media posts, a website story, an e-newsletter story, announcements in stakeholder newsletters, and a series of demonstrations at various stakeholder meetings.

As another example, the Texas RMC system described in Step 1 had become important information for the Texas state submerged lands oil and gas lease sale process by 2013, but it needed to be updated to keep it current and to provide consistent coverage. Prior to 2013, state and federal agencies would separately mark codes on maps for each track they knew had potential environmental restrictions, then the Texas General Land Office would compile the information and make it available to the public through a static map on a website (that is no longer available). Furthermore, issues of concern had changed since 2001, and a thorough revisiting of the definitions of the codes was needed. To accomplish this, a Data Standards Committee (DSC) comprised of about 45 state and federal coastal managers and information science experts from 12 different agencies was formed. Over a year's time, the DSC developed a data-driven process for updating the RMC.

The Texas General Land Office and the Harte Research Institute at Texas A&M University – Corpus Christi conducted 12 workshops during 2014 to formally elicit expert opinion and knowledge from the DSC. The RMC update process had three major steps: (1) updates to the RMC code definitions; (2) identification, compilation, and when needed, development of data layers to determine the codes; and (3) development of an online tool for viewing the RMC. The intensive meetings were 2- to 4-h long and required active participation by the experts representing their agencies and contributing their personal knowledge. Because the work proceeded sequentially and consistent input was needed, it was also important that the same experts attended most or all of the 12 meetings. This required a commitment from the agencies and dedication of individuals and only succeeded because of the common purpose of improving the efficiency and effectiveness of environmental management where economic development is occurring. Laying out the work plan in advance so that participants could see the level of effort that would be required and plan accordingly was also important to achieving success. The result was the compilation of a geodatabase in a web viewer[10] with over 30 geospatial layers identified by the DSC for assigning RMCs to more than 6,400 lease tracts in Texas coastal waters (**Figure 5**). The layers include data on sensitive areas, such as seagrass, flats, and marshes, bathymetry, protected areas, dredged channels, and endangered species distributions to name a few. An online map viewer allows the public to select a lease tract and get a listing of the RMCs as well as links to the definitions of the codes and how they are derived from the geospatial layers.

Account for Technological Realities of the End Users

There can be a tendency in data product development to include the latest and greatest functionality or tool because it is flashy, and it seems like many potential users and developers are talking about it. However, if the technological capacity and challenges of the users are not considered, the resulting tool could easily end up being essentially worthless to the target end user. How the stakeholder will access the information must be taken into account. Sometimes the simplest solution is the best for a particular user or stakeholder group, with complexity added as needed or requested by users.

The VMGD issues a bulletin called the Vanuatu Ocean's Outlook Bulletin (**Figure 6**) that is tailored to help stakeholders within specific sectors, such as fisheries and sea/lagoon farming, to inform planning and security. As not everyone has access to email or the Internet in Vanuatu, sometimes the information included in these bulletins is relayed by telephone. Community outreach personnel, in turn, then spread the information through community meetings and church gatherings. In addition, Vanuatu is a bilingual country, with about 138 different native dialects and three official languages—English, French, and Bishlama. This presents a challenge to accurately communicate climate science messages. It is not easy to simultaneously craft a message that the citizens can understand and that remains true to the scientific facts in such a way that the key messages are not lost or toned down in the process. It is a team effort to go through the products and to make sure that the translations to the three languages keep their meaning and remain consistent throughout. Vanuatu Language Services assists with translating to all three languages. In addition, a vocabulary page explains more scientific and technical terms. The team also receives feedback on Bishlama translations from stakeholders proofreading the climate

[10]https://cgis.glo.texas.gov/rmc/index.html

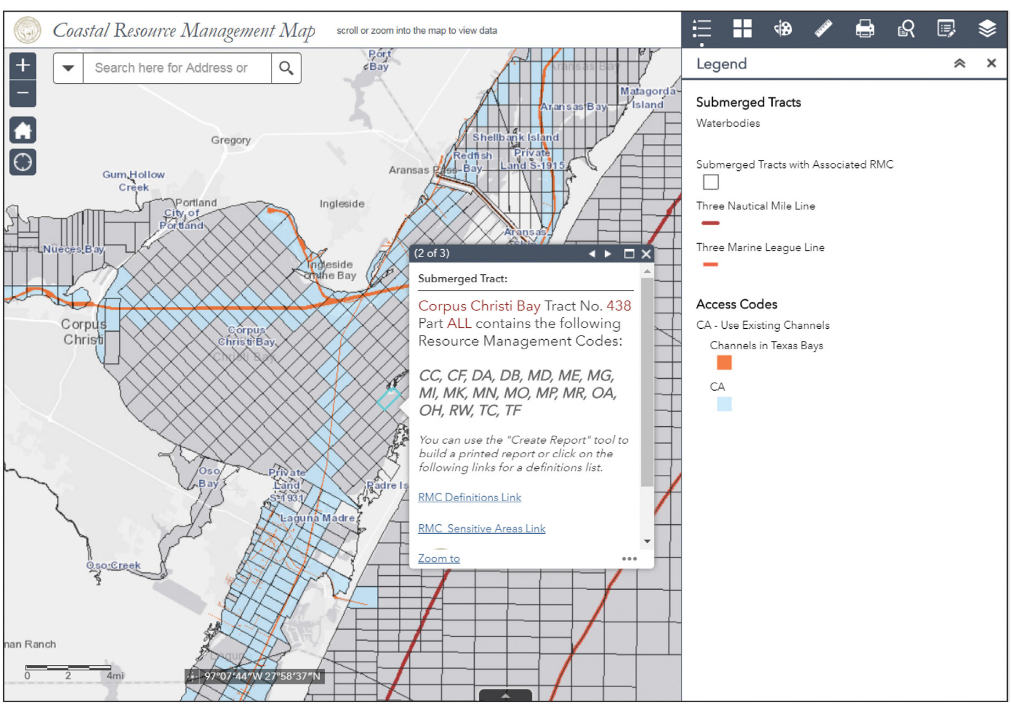

FIGURE 5 | Resource Management Code (RMC) web viewer featuring lease sale nominations and RMC pertaining to type of access limitations. Image courtesy of Texas General Land Office.

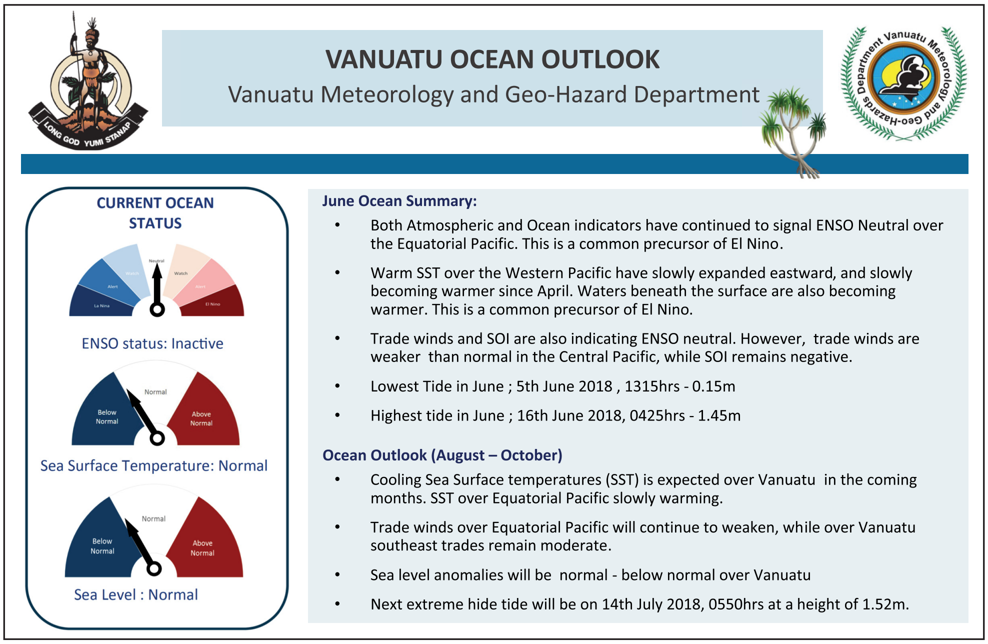

FIGURE 6 | Excerpt from the English language version of the Vanuatu Ocean Outlook Bulletin. Developed by the Vanuatu Meteorology and Geo-Hazards Department, this document provides the community with information helpful for planning efforts in various sectors, such as fisheries. Image courtesy of Vanuatu Meteorology and Geo-Hazards Department.

products before publishing, as it is absolutely vital that their needs are accounted for in the product(s).

Even for those connected to the Internet, the speed of connection and the actual infrastructure are important considerations. This was the case for the resource managers in American Samoa mentioned in Step 1 (see Section "Build Relationships") that were interested in the temperature data from a new PacIOOS wave buoy to help them track and monitor potential coral bleaching events. American Samoa has limited bandwidth, making it hard for residents to check some websites, let alone use a bandwidth-hungry data portal or animated tool. In this case, working with the end users was essential to ensure that they were able to access the resulting product. The local liaison helped PacIOOS determine that the best way to accommodate for low-bandwidth was an automated daily email to a listserv. The PacIOOS data management team wrote a script to feed wave buoy data into a simple daily email that is sent out at the same time every day, near midnight. The liaison checked back with the managers and scientists to verify what to include in the email, and she asked who would like to be added to the listserv. The users noted that even a small thumbnail in the email message would often slow things down or not display correctly, so the content determined to be the easiest to receive and use was text lines of the data collected, with each row of text indicating a separate temperature reading.

These examples highlight the need to take technology needs and limitations into account when developing a new tool and how tailoring products to user needs and requirements does not necessarily mean being overly complex. Sometimes a simple solution is the most impactful. In addition, serving stakeholder needs does not always have to be a long, time-consuming process, especially when the relationships are already well-established. Indeed, the amount of time from the first request from stakeholders in American Samoa to the first daily email to the listserv was under 1 month.

Answer the Right Questions

Working directly with the end users helps to ensure that the right questions are being answered, and that the information provided, as well as the manner in which it is provided, will add value and truly inform user decision-making.

This is illustrated in the La Jolla Cove ASBS Explorer developed by the SCCOOS (**Figure 7**). As described in Step 1 (see Section "Participate on Task Teams"), SCCOOS developers worked hand-in-hand with the core partners comprising the La Jolla Shores Coastal Watershed Management Group, which includes the City of San Diego, the University of California San Diego Scripps Institution of Oceanography, the Department of Environmental Health and Safety, San Diego Coastkeeper, and the California State Water Resources Control Boards. Each designated ASBS along the California coast exists in a complex coastal regime subject to ever-changing land-sea-atmospheric interactions. When the partners approached SCCOOS to develop a tool, it was important to learn what questions needed to be answered in order to determine what data was needed. It became clear that they needed to understand the physical environment within and surrounding the La Jolla ASBS to address management questions such as whether changes observed were due to natural variability or anthropogenic impacts.

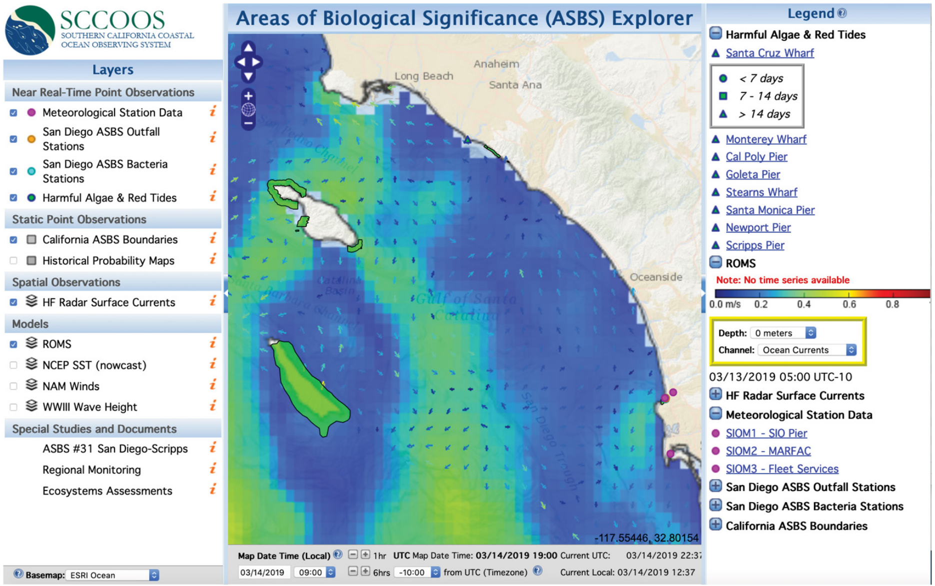

FIGURE 7 | SCCOOS Areas of Biological Significance (ASBS) Explorer tool provides users with a comprehensive interactive map showing critical coastal areas in California along with ocean observations. Image capture from March 14, 2019, is layered with the Regional Ocean Model System that shows ocean currents at 20 m depth, High Frequency Radar surface currents, harmful algae and red tides from harmful algal bloom monitoring stations, and the California ASBS boundaries. Meteorological station (pink circle), piers (blue triangles), and outfall stations can also be accessed through the tool. The ASBS Explorer is intended to help managers and the public monitor impacts on ASBS locations in California, specifically the San Diego metropolitan region. Image courtesy of SCCOOS.

The SCCOOS team worked with the core end users to design a modular, problem-driven application that builds upon different standards and protocols. Emulating existing ocean observing system web portals for ease of navigation and familiarity, the design team used open source formats and protocols to enable access to varying structures and distributed data sources. Since some of the data shown on the website are derived from sources other than SCCOOS, the goal was to access services or data directly instead of hosting copies. This format allowed for varying data types enabling a customized portal. The ASBS Explorer was designed to establish the infrastructure needs and generate a conceptual design that is required for long-term assessment of ASBS performance and related management decisions. The end product is an award-winning, usable, online information system for a range of users. In 2014, the California Assembly Speaker Toni Atkins, the County of San Diego, and San Diego Coastkeeper honored SCCOOS with World Oceans Day and Coastal Champion Awards for their commitment to ensuring the partners have a "top-notch technology" for the ASBS. Designated by the State of California Water Board, ASBS are areas that host aquatic communities that require protection from alteration of the natural water quality. In order to protect these biological communities, sampling of water quality measurements have been regulated to determine alterations in the environment. One of the primary questions for an ASBS is what waters, and from where, may be impacting the ASBS causing any fluctuations in the water quality. The ASBS Explorer enables stakeholders to answer these questions for proper management of these special areas.

Consider the Timing of Product Delivery

Knowing your stakeholders and their specific delivery needs, including the timing of delivery, can help ensure product utility. For example, SECOORA's How's the Beach tool (**Figure 8**) delivers a beach water quality forecast in time to inform daily public health advisories. The South Carolina Department of Health and Environmental Control monitors bacteria levels in nearshore swimming beach waters with water samples analyzed by an approved laboratory. On average, 24 h pass from sample collection to the time the results are received by the responsible agency. The agency issues public health advisories if bacterial levels exceed legal limits (defined by the U.S. Environmental Protection Agency, EPA). However, due to the testing time lag, advisories are issued well after the problem occurred (i.e., beach swimming advisories for a given day were based on the previous day's water quality tests).

South Carolina beach managers realized the need for a preemptive forecasting tool to issue public health advisories. Managers also felt that the general public should be informed to make decisions about going to the beach versus other activities (e.g., swimming pool, miniature golf, other entertainment options). In an effort to better inform local beach managers and public health officials, tourism officials, and the public about potential health risks, researchers and developers at the University of South Carolina and University of Maryland created the How's the Beach forecasting tool[11]. This tool incorporates land use practices, meteorological and oceanographic data, along with National Weather Service (NWS) products to forecast

[11]http://howsthebeach.org/

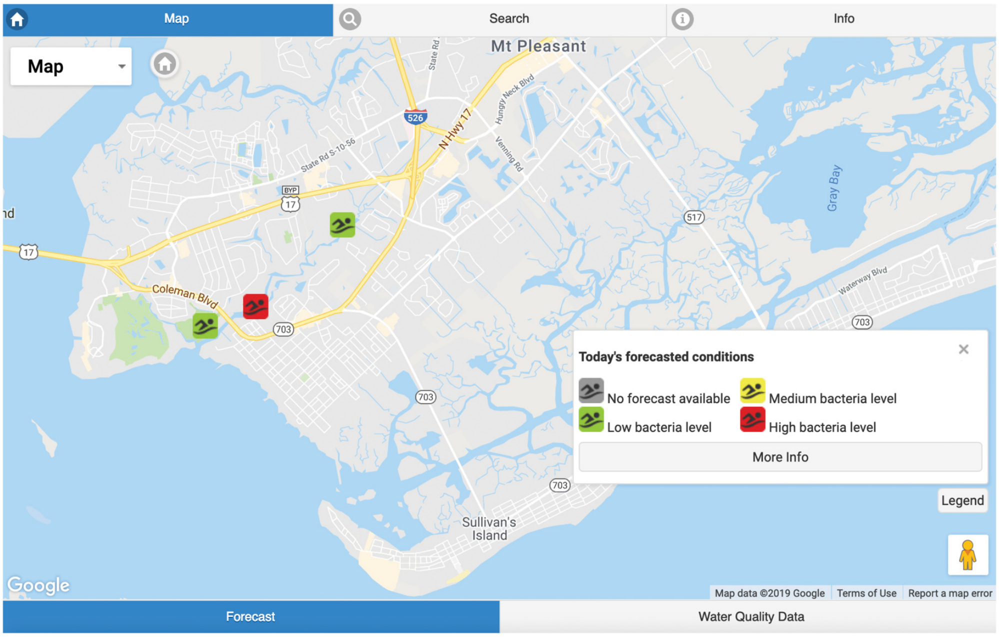

FIGURE 8 | Example display of How's the Beach daily forecast of Enterococci bacteria levels for Shem Creek, SC. From here, users can view forecasts and access current and historical sampling data and high-resolution aerial imagery of specific sampling locations. Image courtesy of SECOORA.

bacterial concentrations at area swimming beaches. Due to the support and enthusiasm from federal, state and local agencies for the response to the timely information, the forecasting efforts have expanded beyond the original scope to become a SECOORA product development initiative. Advisory agencies in North Carolina and Florida requested that the modeling effort and associated tools be developed for target areas in their states so that timely notices can also be provided.

Tailor Delivery for Different Audiences

Often, in order to make the ocean observing or forecast data relevant and useful for different types of stakeholders, the same information just needs to be presented in slightly different ways. With three levels of products, the How's the Beach tool is tailored to inform state agencies, the general public, and shellfish managers. The first product is for state agencies responsible for issuing beach advisories. Forecasts are run daily, coordinated with availability of NOAA NWS NEXRAD precipitation data. A report is emailed to beach managers at 9:03 AM daily.

The second product is for the general public (see footnote 11). This product is delivered via web interface or a phone app, and it was developed at the behest of the beach managers who wanted an easy way for the public to view the alerts. While the primary stakeholder is state agencies responsible for environmental quality monitoring, the project team hosted a public stakeholder workshop in Sarasota, FL to solicit feedback so they could tailor the app to meet broader needs.

The third product consists of scripts written to support shellfish managers who close harvest areas in South Carolina based on threshold rainfall values. For example, some managed areas are closed to shellfish harvest when more than 4 inches of rain falls within a 24-h period. State-level shellfish managers contacted the project team to request a data analysis report for the NEXRAD precipitation data. Shellfish managers provided geographical areas of interest, depicted as polygons, where they need rainfall amounts and the associated thresholds. These polygons are used to clip out relevant NEXRAD data and summarize rainfall for areas within the polygon. A summary report of the previous 24 h of precipitation for each shellfish harvesting area is provided to shellfish managers each morning.

Rely on Existing Relationships to Guide the Process

In the Pacific Northwest U.S., the Northwest Association of Networked Ocean Observing Systems (NANOOS) was approached by the Padilla Bay National Estuarine Research Reserve to collaborate on an application (app) that would serve water quality data of interest to shellfish growers. In 2004, the resulting site was based on input from the growers about how to best present the data, such as temperature in degrees Fahrenheit and different temporal views (e.g., 24 h, 3 days, 14 days) to visualize features or trends. Subsequently, to address industry requests, these features were incorporated into NANOOS' own data portal, the NANOOS Visualization System[12], as options.

As NANOOS transitioned the Shellfish Growers' App (**Figure 9**) to their Visualization System, a meeting was held with a small focus group of growers (~6–8) hosted at one of the growers facility, where the NANOOS software engineer, outreach staff, and director met with the growers to try out options, and hear what features and information the growers wanted. This resulted in NANOOS staff learning new things that they did not

[12]http://nvs.nanoos.org/Apps

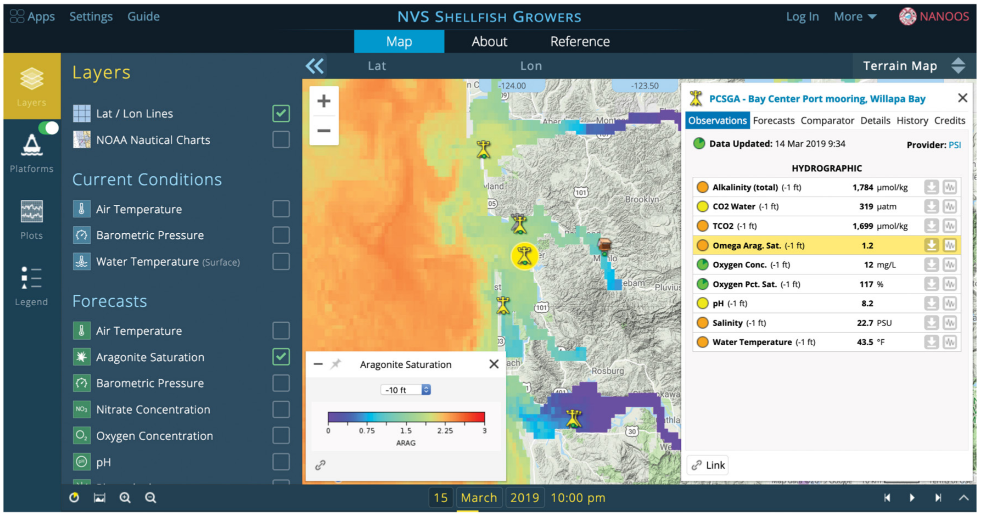

FIGURE 9 | Screenshot of the NANOOS Visualization System "Shellfish Growers" web app. From this page, users can view both forecast model output and near real-time observations. Also added was the ability to view different timescales of the measurements (e.g., oxygen, pH, and salinity) to see how these may co-vary with time. The user selects the units, timescale, and other variables. Other user-selected tabs provide additional details, history, credits, and links to the data provider. Image courtesy of NANOOS; background color image is from a LiveOcean forecast of aragonite saturation state.

anticipate. For instance, regional airport rainfall data is important because closures are called when non-point storm water runoff potentially carries bacteria to shorelines. Also, technology had advanced such that mobile phone apps were now common and offered a better way of data delivery, due to the ability to check data while in the field. The focus group was consulted, and then presentations and one-on-one demos and feedback at grower conferences allowed for more feedback. Being flexible, willing to change original designs, and listening has resulted in a new and improved app. Pacific Coast Shellfish Growers Association Executive Director Margaret P. Barrette explains, "This current generation of shellfish farmer is reliant upon data and services from NANOOS. Checking the NANOOS app before seeding a beach or filling a settling tank has become standard practice."

The relationship of trust (Step 1) was critical in the development of the NANOOS app—to know each others' needs and capabilities, and to have the long view on how to keep needs met. With the advent of ocean acidification awareness and impacts to shellfish growing, now both real-time data from buoys and moorings from a host of partners and 3D modeling forecasts from a new LiveOcean model[13] were incorporated. With this added forecast feature to the desktop version of the Shellfish Growers app[14], also came additional complexity. Growers requested guidance on features they may not have discovered on their own. This resulted in a slideshow guide that pops up on first use of the app and then can be consulted thereafter or turned off.

Clearly, while the mechanisms described above for Step 2 translate across various situations, a program is not going to employ all of them during the development of any one product. The context of the data product, in particular the stakeholder group(s) and their need(s), should help determine how to approach product development. For example, NANOOS has followed a similar process to the one described above for shellfish growers with other stakeholder groups, such as maritime operators, recreational boaters, tuna fishers, surfers, and beach users. But other groups that NANOOS serves, such as managers and agencies responsible for harmful algal bloom and tsunami responses, needed a somewhat different process for product development. As NANOOS has developed relationships with these stakeholders, they use the knowledge gleaned during their tailored engagement to determine the most effective and efficient steps to utilize for successful product development.

Overall, the creation of data products, tools, and services requires end user engagement from product initiation. Developing with end user input ensures the efficient and effective use of resources (in time, effort, and funding).

Step 3: Iterative Engagement With Users to Assure Data Products Remain Relevant

Stakeholder-driven projects require iterative stakeholder engagement and feedback in order to remain relevant and useful to the target audience. When feasible, it is helpful for the stakeholder community to become enmeshed with the organization leading the effort so that the user needs also become the needs of the product team. This fosters long-term commitment to the project, and the stakeholders can even become advocates for the tool and the organization.

Remain Engaged With Stakeholders

As the overall intent of the products being produced is to help inform decision-making, it is important to tell stories about

[13]http://nvs.nanoos.org/ShellfishGrowers?action=overlay:liveocean_ph

[14]http://nvs.nanoos.org/ShellfishGrowers

how people use the information to expand their knowledge and make decisions. For many data products, it is useful for first-time users to be provided with concrete examples of how to use the information so they understand the benefits and limitations of the product.

In Vanuatu, VMGD hosts an annual National Climate Outlook Forum to engage sector-specific stakeholders and the Pacific Climate Outlook Forum for all climate seasonal forecasters. These venues provide space for stakeholders to share their experiences, share ideas, and improve their processes for information dissemination and understanding. These meetings are also venues to continue to engage users, update efforts, and ensure that data products remain relevant.

Prepare for a Long-Term Commitment

Organizations that create data products should enter the process with an understanding that they are making a long-term commitment to stakeholders. Product development and stakeholder engagement does not end when the product is made available or implemented. For a project to remain relevant, users have to remain engaged, and tools and applications often need to be updated to take advantage of technological advances. Stakeholders should review updated websites, tools, and applications before changes are released. It should be clear who has the responsibility for supporting these efforts, especially with regards to funding.

One long-term example is the SECOORA Marine Weather Portal (**Figure 10**). The development of regional coastal ocean observing systems in the early 2000s, as part of the U.S. IOOS initiative, provided increased meteorological and oceanographic data over and beyond the data that NOAA and other federal agencies provided. One of the challenges faced by IOOS-funded organizations was how to aggregate data from multiple sources in a meaningful way for stakeholders. An early data aggregation project was a small-scale web design initiative titled the "Carolinas Coast." The Carolinas Coast tool launched in February 2005, and was a collaborative effort between the NWS Weather Forecast Office in Wilmington, NC, the University of North Carolina Wilmington, and the University of South Carolina. The team re-engineered the Wilmington and Charleston Weather Forecast Offices' marine observations and forecast web pages. The new site incorporated data from moorings off North Carolina and South Carolina and displayed NWS marine weather and forecast data in a consolidated format across multiple NWS coastal coverage areas.

Based on the success of the Carolinas Coast website, in 2007, the team expanded their coverage area throughout the Southeast U.S. and the Gulf of Mexico and rebranded as the Marine Weather Portal (MWP; Dorton et al., 2009), a site for mariners (from the casual boater to the commercial fisherman). In 2016, the MWP[15] was further improved. The map interface was upgraded, and a mobile version was developed for those who connect via cell phone. Additionally, NWS offices across the southeast provided the development team with new products to incorporate (e.g., probable storm surge impacts, public health advisories, and adding forecasted data to graphs along with observed data so that users

[15]https://mwp.secoora.org

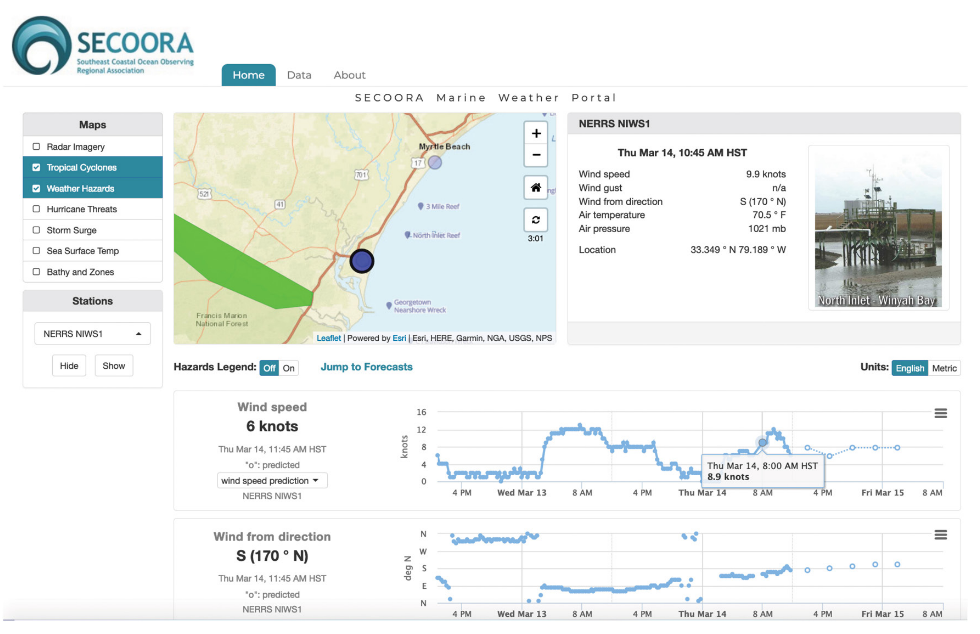

FIGURE 10 | The SECOORA Marine Weather Portal map interface allows users to toggle on/off layers (e.g., weather hazards, sea surface temperatures, and hurricane threats). The dots on the map represent real-time stations (e.g., buoys, water level stations) that users can click on to see recent observations and forecasts for that location. Individual station pages, such as shown in this figure, allow users to graph the most recent data and observe trends in the weather and sea state data. Image courtesy of SECOORA.

can identify trends) and ideas for future enhancements (e.g., adding virtual buoys, other product delivery methods) (Dorton et al., 2018).

Stakeholders have been engaged throughout the site development since the early 2000s in numerous ways, including: focus group meetings; questionnaires distributed to focus groups; NWS surveys located on the NWS websites; and presentations at marine community meetings and boat shows. One of the keys to the success of the MWP is how it is user-driven and built upon the success and lessons learned from the localized Carolinas Coast initiative and early versions of the MWP. The MWP outreach and data management personnel actively engage the stakeholders to get comments and feedback on the product and address end user needs in collaboration with the NWS. The MWP is an example of how product development does not stop with the launch of a website or creation of a new product. The MWP project team has invested in information technology and data management structures that allow for enhanced product robustness and reliability.

Expand Functionality as Requested

As questions, stakeholders, and technologies evolve, so too may the needs and requests from end users. Once a data product is integrated into the decision-making of end users, they can start to imagine the potential for new data and functionalities.

The NERACOOS climatology tool (as described in Steps 1 and 2, specifically Section "Attend Stakeholder and Partner Meetings" and Section "Employ a Formal Product Development Process When Appropriate") has been so well received by fishermen and fisheries resource managers since it was initially launched in 2011, that these groups have asked for expanded functionality on the site. New functionality requests included the ability for the following: to define the time period(s) to calculate the climatology statistics; to plot multiple water depths and locations at the same time; and to include other historical climatology data. The ability to define date ranges and include other data types, such as satellite data, is helping with decision-making for multiple user groups. For example, fishermen can better plan when to fish or lobster based on ocean temperature; lobster processing facilities can plan for fluctuations in catch, resulting in better use of personnel hours; and, resource managers are able to monitor catch data and also identify changes in catch (both abundance and species). These examples also highlight how tools developed for stakeholders can have an impact not only on individual decision-making processes but also on local economies.

Be Open to Unexpected Outcomes

Iterative engagement with the users can also lead to new insights and products, often unexpected. In American Samoa, users have found the daily email product (described in Step 2, Section "Account for Technological Realities of the End Users") with the PacIOOS wave buoy SST data to be extremely helpful for the intended design: to easily monitor the ocean conditions for corals, especially during El Niño years. With this information, managers and scientists are able to better plan their monitoring operations. Hideyo Hattori, NOAA Coral and Coastal Zone Management Liaison in American Samoa explained, "Coral bleaching has significantly increased in recent years, becoming more frequent and more intense. Receiving daily SST data from PacIOOS provides us with a snapshot of the actual conditions and serves as an effective indicator to anticipate bleaching events." When the SST values increase, NOAA and partners increase their surveying efforts to track and monitor coral health around the islands.

An unexpected outcome of this collaborative effort and resulting product, which had many people pay so close attention to the SST data, was a discovery of what appears to be warm plumes of water recorded by the buoy. After watching the data for some time, managers and scientists agree that it is likely *not* due to an increase in the thermal energy of the buoy from absorbing solar radiation. In May 2017, once the El Niño conditions ended, and the imminent threat of coral bleaching passed, stakeholders in American Samoa asked (again through the local liaison) if PacIOOS could keep sending the daily emails, but also create an alert system that notified those interested when the SST reaches a specific threshold (i.e., more than a 1.5 degree Fahrenheit increase over the course of a day) in order to help track the occurrence of the warm plumes. After a few iterations with stakeholders, PacIOOS developed this additional tool, which is also distributed via email listserv. This is another quick, simple solution that helps resource managers do their job more efficiently. Developed after a couple of years of the initial tool, this new tool includes all the important information (i.e., the degree increase over the past date) in the subject line. Users do not even have to open the email to glean the information desired.

Late in 2017, partners were able to use the information and knowledge gathered through these simple tools to secure external funding from the American Samoa Power Authority and the American Samoa Renewable Energy Committee to purchase and attach temperature loggers along the wave buoy mooring line. The PacIOOS liaison worked with a student from Pacific Horizons High School and Crux Diving to attach the sensors to collect temperature data at different depths. Researchers suspect hydrothermal fluid may be venting from the fracture zone at the seafloor. If geothermal venting is confirmed, further studies are planned to determine whether this is a potential source of geothermal energy for American Samoa.

Evaluate the Product on a Regular Basis

Even once a product is developed, the work is never complete. In addition to ongoing maintenance, engagement, and outreach, it is important to evaluate the product on a regular basis. Depending on the product and the objectives associated with it, there are various metrics that can be employed to evaluate a tool. User metrics, such as the number of users or sessions per tool can be obtained with various platforms (e.g., Google Analytics), but as utility for a specific user group is often the objective for a tool, such quantitative metrics do not always tell the whole story. Take the American Samoa listserv as an example. If PacIOOS were to evaluate the effectiveness of this tool based solely on the number of people signed up for the listserv, the program would quite possibly see a relatively low number and determine it was not worth maintaining. However, as the objective of the listserv was to help the local resource managers monitor the SST to guide their monitoring plans and decision-making, a different, more qualitative measure is used: namely, is the target audience using the tool and satisfied with its performance?

Similarly, the resources required to develop and maintain the product should be assessed regularly. Spending a significant amount of resources on a single user, for example, might not be the best use of a program's resources. However, if the single user is a federal agency that saves lives with the information or product provided (e.g., U.S. Coast Guard), a different metric (e.g., need expressed by an operational partner) may be necessary.

Ideally, the scale and the utility of a product should be taken into account before the product is developed, but these considerations also need to be revisited during product evaluation. Evaluation should also include scope management, ensuring that a program stays true to the stakeholder-driven philosophy—staying focused on the original purpose and audience and not getting caught up in the trap of thinking, "If we build it, they will come." If one stakeholder group asks for a product, it is important not to make the assumption that everyone needs it. Furthermore, if a product does not successfully address stakeholder needs, or is replaced by other developments, the program should not continue sinking resources into it. Rather, it benefits the program to view this as an opportunity to free up resources to take on new efforts to make new and better products for stakeholders.

There are numerous ways to evaluate a product. The objectives of a particular product should guide which type of evaluation process to use. For example, since the How's the Beach tool has several related products to serve a varied set of stakeholders, SECOORA has taken a more formal approach by forming technical working groups to evaluate the products, to refine the products as needed, and to continue stakeholder engagement. The EPA Virtual Beach Advisory Committee, including representation from the SECOORA region, uses federally published reports to help them determine potential future public health forecasting efforts. A second regional working group under SECOORA is responsible for iterative engagement and data product review. This group is hosting a workshop in late-2018 to discuss needs and next steps with users such as U.S. Geological Survey, state agencies with beach management and shellfish management responsibility, EPA Virtual Beach modeling group, project partners from the University of South Carolina, the University of Maryland Center for Environmental Science, SECOORA, the National Estuarine Research Reserves, and local Waterkeepers. Both working groups are tasked with reviewing the model (inputs and outputs) and products for each audience, providing feedback to SECOORA, and guiding product and tool refinement as well as methods of delivery.

Build Iteration and Outreach Into Budgets and Work Plans

Iteration—remaining engaged with stakeholders, adding functionalities, committing long-term, and evaluation—all require resources of an observing program. Similar to the best practice of including tailored stakeholder engagement (Step 1) into the project or program budgets and work plans, the resources required for successful outreach as well as iterative engagement and product refinement also need to be taken into account at the outset. In order to help assure a program's ability to implement this process, it is advisable to include the recurring costs for a particular data product into project budgets as much as possible. Furthermore, once a particular project budget is closed out, the program needs to have a plan for how it will absorb the recurring costs.

For example, Hawai'i Sea Grant and the State of Hawai'i Office for Conservation and Coastal Lands asked PacIOOS to be a partner on a proposal that included funding for PacIOOS to develop the Hawai'i Sea Level Rise Viewer[16] (**Figure 11**). The resulting viewer is based on partner and user input and requirements for both usability and to meet the needs of the state agencies fulfilling a mandate from the State Legislature. Project funding also included several months for partners to provide trainings and presentations on the viewer and to collect additional feedback for PacIOOS to maintain, update, and refine the tool. Since December 2017, when the tool was released in concert with the State Sea Level Rise Vulnerability Report to the State Legislature, the project partners have been presenting and conducting outreach to numerous groups, agencies, and government councils on the Statewide report and the associated viewer developed by PacIOOS.

Strong, long-term relationships (Step 1, Section "Build Relationships") between the project partners enabled PacIOOS to reinforce the need for funding support to collect iterative stakeholder input, to continue to refine and update the viewer, and to have the lead partners carry out the trainings and presentations. In this way, the product's continued relevance and utility are built into the overall project objectives, activities, and budget. To date, the viewer has been well received by the target audiences (including the State Climate Commission, other policymakers, and county planners) as well as the interested public. Partners continue to receive numerous requests to demonstrate the viewer, and they are receiving positive feedback and learning about more stakeholders that are utilizing the tool for their work. Funding in the project budget is enabling this essential iterative process.

SUMMARY

Let Stakeholders Drive the Process

Successfully and efficiently addressing the unique challenges of coastal communities through observing systems necessitates a process that accounts for the diversity among users and iteratively integrates that understanding throughout the product development life cycle. Promoting a stakeholder-driven philosophy, the three-step process described in this paper emphasizes engagement with the end users before any product development begins. It is imperative to continue engagement through product development, iteratively assess the product with stakeholders, and respond to their feedback as they use

[16]http://www.pacioos.hawaii.edu/shoreline/slr-hawaii/

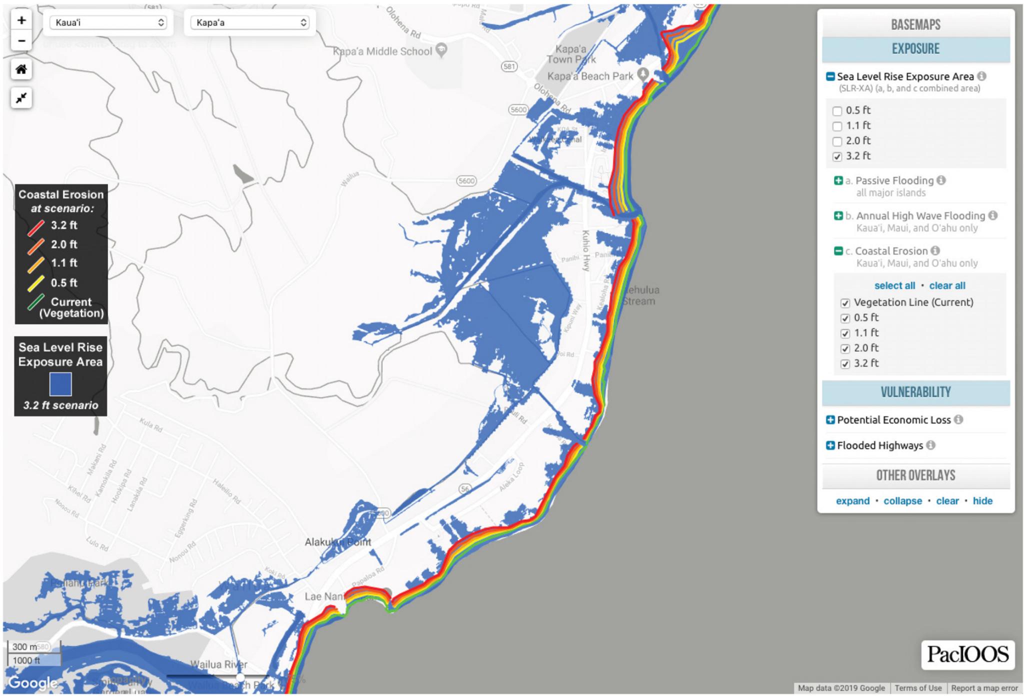

FIGURE 11 | The Hawai'i Sea Level Rise Viewer that PacIOOS developed is a companion tool to support the State of Hawai'i Sea Level Rise Vulnerability and Adaptation Report. Policy-makers, planners, homeowners, and the public can explore exposure and vulnerability layers of four sea level rise scenarios. Users can view the geographic extent of three chronic flooding hazards (i.e., passive flooding, annual high wave flooding, and coastal erosion) separately or as an overlay. The image shows the overlay sea level rise exposure layer (dark blue) for the 3.2 ft. sea level rise scenario, and the reach of coastal erosion for each sea level rise scenario (red, orange, yellow, and green lines). Image courtesy of PacIOOS.

a new tool. While the content herein may seem obvious or simplistic to some, the reality is that far too many data products are still developed without going through most, or even any, of the essential steps described above. To be truly effective in delivering value to coastal communities, observing systems must evaluate how they connect their stakeholders to coastal and ocean observing data.

Although "steps" imply a linear process, the approach we describe is best imagined as an iterative, non-linear process. Indeed, the approach described in this paper is a continuum in which the three steps overlap and blend into each other as well as iteratively repeat (**Figure 1**). Even before the first step, though, it is important to set or affirm the *intention* to operate a stakeholder-driven process. Within this paradigm, the approach described in this paper takes hold. In addition, we recognize that this approach sits within a larger context of well designed coastal and ocean observing systems that are science-based and policy neutral. While it is beyond the scope of this community white paper, it is worth noting that the placement of observing assets must take into account both societal needs as well as scientific design and environmental processes. The process to develop tailored products that utilize the data collected from such assets in order to address stakeholder needs is the focus of this paper.

As the resources available to support observing systems and related programs are not sufficient to address all the societal needs, it is essential to be efficient with the use of the resources available. Engaging with stakeholders throughout the conceptual, design, implementation, and evaluation phases of data product development helps to ensure that resources are efficiently managed and utilized. Indeed, the entire process needs to be carefully considered at the outset of product development. It is vital, for example, for organizations to ensure that they have a plan to sustain and refine the product, should it be successful in the eyes of the stakeholders.

The diverse examples peppered throughout this paper highlight how various coastal and ocean observing programs implement the stakeholder-driven process to develop tailored data products. **Table 2** shows the strategies employed for each step of the process during the product development life cycle for each of the examples discussed. Each data product used specific (and not all) of the strategies discussed; however, each example employed strategies from each of the three steps of the overall process. The programs tailor user engagement to learn about stakeholder needs. This engagement helps define and refine data products based on end user requirements, and iteratively engaging with stakeholders ensures that products remain relevant. While there are countless more examples that could demonstrate the concepts included herein, those included also feature the breadth of geographic, conceptual, and stakeholder reach of data products built upon coastal and ocean observations. We hope the best practices and successes described in this community white paper inspire others to

TABLE 2 | A matrix of the strategies discussed in this paper for each of the three-step process against the data product examples discussed in this paper.

		Alaska Water Level Watch	GANDALF	NANOOS Shellfish Growers App	NERACOOS Ocean Climate Tool	American Samoa SST email	Hawai'i Sea Level Rise Viewer	How's the Beach?	Marine Weather Portal	ASBS Explorer	Texas GLO RMC web viewer	Vanuatu Ocean Outlook
Step 1: Tailor engagement to identify user needs	Build relationships	o	o	**X**	o	**X**	o	o	o	o	o	**X**
	Follow cultural protocol	o					o	o				**X**
	Attend stakeholder and partner meetings	o	o	o	**X**	o	o	o	o	o		o
	Host workshops	**X**	o	o	o		o		o	o	o	o
	Participate on task team	o		o		o	o	o		**X**	**X**	o
	Include engagement in program budget	o		o	o	o	o		o		o	o
Step 2: Design and refine data products with users	Utilize informal product development, as appropriate	o	**X**	o		o				o		
	Employ a formal product development process, as appropriate	o			**X**		o	o	o		**X**	
	Account for the technological realities of the end users	o	o	o	o	**X**	o	o	o	o		**X**
	Answer the right questions	o	o	o	o	o	o	o	o	**X**	o	o
	Consider the timing of product delivery		o	o		o		**X**				
	Tailor delivery for different audiences	o	o	o				**X**				
	Rely on existing relationships to guide process	o	o	**X**	o	o	o				o	o
Step 3: Iterative engagement with users	Remain engaged with stakeholders	o	o	o	o	o	o	o	o	o		**X**
	Prepare for a long-term commitment	o	o	o	o	o	o	**X**	**X**	o	o	o
	Expand functionality as requested	o	o	o	**X**	o	o		o	o	o	
	Be open to unexpected outcomes		o	o	o	**X**	o	o	o	o		
	Evaluate product on a regular basis	o	o	o	o	o		**X**	o	o	o	o
	Build iteration and outreach into budgets and work plans	o	o	o	o	o	**X**	o	o		o	o

*Each data product used specific (and not all) of the strategies discussed; however, each example employed strategies from each of the three steps of the overall process. A bold, capital "**X**" signifies that the strategy was employed for product development and highlighted as an example in this paper; a small "o" signifies that the strategy was employed for product development, but not discussed in detail for that particular product in this paper.*

enhance their engagement with stakeholders at every stage of product development.

Looking Forward: Aspirations for the Coastal and Ocean Observing Community for the Next 10 Years

While each coastal and ocean observing system or program may have slightly different missions, the overarching goal is to address societal needs: to improve the lives and livelihoods of stakeholders. As the number and types of observations continue to increase across the globe, we aspire for stakeholder-driven products to be the norm, rather than the exception. Funding should no longer support the development of tools without a demonstrated stakeholder need. Developing a tool, and *then* seeking stakeholders that "need" it is simply no longer acceptable. Resources, both fiscal and personnel, are too limited to spend on such efforts. The costs of such actions are too great, especially when the potential rewards of stakeholder-driven efforts are so high.

We envision a future in which data sets are increasingly interoperable, allowing for more integration and comparison among existing and new datasets. This will create new opportunities for stakeholder-driven data products. Ensuring that the resulting data products, as well as the observing system designs, are stakeholder-driven will greatly enhance societal benefit. Furthermore, we advocate for data products to be built on open source platforms that are freely available—placing collaboration and mission-driven activities before profit and competition. Open source applications enable programs to stretch resources and cross-pollinate, rather than duplicate, ideas and efforts, which in turn enables observing systems to increase the reach and benefit to their stakeholders.

While not explicitly discussed in this paper, the issue of increasing capacity in areas with less coastal and ocean observing assets, data, and community experience is an important theme globally. With the understanding that resources are limited, we encourage the broader community to use the next decade to innovate, collaborate, and stretch the boundaries of observing to identify and address stakeholder needs. Those with fewer observing assets still have much to offer in terms of willing partners, coastal and ocean access, connections with communities, ideas to address needs, fiscal resources, and more. Technical training opportunities, internships, collaborative workshops, and listening sessions are some ideas that come to mind, but there are certainly others that can help bridge and fill the observing gaps across the globe.

There is an opportunity to fill observational gaps by linking an enthusiastic citizen base with technological advancements. The potential to fill or augment data gaps with information collected by stakeholders and citizens has only recently begun to take shape. There is also great potential for stakeholders to help direct the data collection to address specific needs under a set of predefined standards and protocols. We envision a future where interested and informed participants have access to the tools and expertise necessary to rapidly analyze and synthesize data and data products that integrate data from multiple sources. Global awareness of the vital importance of coastal and ocean information is growing, and communities at all levels are increasingly interested in getting involved. If these stakeholders can see that they truly have a voice and are the drivers behind the design and implementation of observing systems, their support and participation in the process will continue to flourish. It is up to all of us in the global coastal and ocean observing community to ensure that this is the reality that stakeholders experience.

AUTHOR CONTRIBUTIONS

MI, JD, JN, MY, and JG contributed to the conception and design of the manuscript and provided the language that served as the foundation for the manuscript development. MI led the review, the design, and the development of the manuscript, with much assistance from JD. MI and JD gathered and incorporated larger community input for the manuscript. TS, BK, and RC helped fine-tune and craft the messages within the manuscript and wrote specific sections based on their experiences. All authors contributed to manuscript revision and have read and approved the submitted version.

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REFERENCES

Bishop, R., and Glynn, T. (1992). He kanohi kitea: conducting and evaluating educational research. *N. Zeal. J. Educ. Stud.* 27, 125–135.

Bourne, L. (2016). Targeted communication: the key to effective stakeholder engagement. *Proc. Soc. Behav. Sci.* 226, 431–438. doi: 10.1016/j.sbspro.2016.06.208

Dorton, J., Galvarino, C., Porter, D. E., and Hernandez, D. (2018). "Integrating marine weather data, forecasts, and user assessments to upgrade the Marine Weather Portal," in *Proceedings of the MTS/IEEE OCEANS 18 Conference*, Charleston, SC.

Dorton, J., Subramanian, V., Galvarino, C., and Porter, D. E. (2009). "Ocean observing: linking observations to the NWS and marine community," in *Proceedings of the MTS/IEEE Oceans 09 Conference*, Biloxi, MS.

Edwing, R. (2015). *Approval of Revised Policy for Management and Dissemination of External Source Water Level Data, Memorandum*. Silver Spring: NOAA.

Iwamoto, M. M., Langenberger, F., and Ostrander, C. E. (2016). Ocean observing: serving stakeholders in the Pacific Islands. *Mar. Technol. Soc. J.* 50:3. doi: 10.4031/MTSJ.50.3.2

Liu, Y., Kerkering, H., and Weisberg, R. H. (eds) (2015). *Coastal Ocean Observing Systems*. Amsterdam: Elsevier.

Mulcahy, R. (2013). *PMP Exam Prep,* 8th Edn. Hopkins, MN: RMC Publications, Inc.

NetCDF 4.6.2 (2019). *The netCDF Interface*. Available at: https://www.unidata.ucar.edu/software/netcdf/docs/netcdf_introduction.html (accessed February 28, 2019).

Project Manager (2019). *What is a Stakeholder?* Available at: https://www.projectmanager.com/blog/what-is-a-stakeholder (accessed February 28, 2019).

Smith, L. T. (2004). *Decolonizing Methodologies: Research and Indigenous Peoples. 7th Impression*. New York, NY: Zed Books Ltd.

Willis, Z. (2015). "National Ocean Observing Systems in a Global Context," in *Coastal Ocean Observing Systems*, eds L. Yonggang, K. Heather, and R. H. Weisberg (Amsterdam: Elsevier Science & Technology), 11–25. doi: 10.1016/b978-0-12-802022-7.00002-x

Worsley, L. M. (2016). *Stakeholder-Led Project Management: Changing the Way We Manage Projects*. New York, NY: Business Expert Press.

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The Global Integrated World Ocean Assessment: Linking Observations to Science and Policy Across Multiple Scales

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In 2004, the United Nations (UN) General Assembly approved a Regular Process to report on the environmental, economic and social aspects of the world's ocean. The Regular Process for Global Reporting and Assessment of the State of the Marine Environment, including Socioeconomic Aspects produced the first global integrated assessment of the marine environment in December 2016 (known as the first World Ocean Assessment). The second assessment, to be delivered in December 2020, will build on the baselines included in the first assessment, with a focus on establishing trends in the marine environment with relevance to global reporting needs such as those associated with the UN Sustainable Development Goals. Central to the assessment process and its outputs are two components. First, is the utilization of ocean observation and monitoring outputs and research to temporally assess physical, chemical, biological, social, economic and cultural components of coastal and marine environments to establish their current state, impacts currently affecting coastal and marine environments, responses to those impacts and associated ongoing trends. Second, is the knowledge brokering of ocean observations and associated research to provide key information that can be utilized and applied to address management and policy needs at local, regional and global scales. Through identifying both knowledge gaps and capacity needs, the assessment process also provides direction to policy makers for the future development and deployment of sustained observation systems that are required for enhancing knowledge and supporting national aspirations associated with the sustainable development of coastal and marine ecosystems. Input from the ocean observation community, managers and policy makers is critical for ensuring that the vital information required for supporting the science policy interface objectives of the Regular Process is included in the assessment. This community white paper discusses developments in linking ocean observations and science with policy achieved as part of the assessment process, and those required for providing strategic linkages into the future.

Keywords: marine environment, ocean observations, ocean-policy interface, ocean literacy, integrated assessment, sustainable development goals

INTRODUCTION

The ocean is vital to all life on Earth, providing countless benefits to humans, with these benefits termed "ecosystem services" (Costanza et al., 1997; Covich et al., 2004; Barbier, 2012). Some of the benefits provided by the ocean are delivered naturally and are known as regulating and supporting ecosystem services. Examples of these services include the functioning of the hydrological cycle, the absorption of carbon dioxide as part of the carbon cycle and the coastal protection offered by many coral reefs (Duke et al., 2007; Palumbi et al., 2009; Barbier, 2017). Other ecosystem services are obtained as a result of human activity to acquire the benefits and are termed provisioning ecosystem services. An obvious example of a provisioning service is the food provided by capture fisheries, which provides significant amounts of the animal protein in human diets – in some regions more than 50% (Hall et al., 2013; FAO, 2018). Globally, coastal and marine habitats have been estimated to provide over US$14 trillion worth of ecosystem services per year (Costanza et al., 1997), however, the challenges in quantifying the value and economic benefits derived from such services mean that there are many varying values placed on services provided (see Barbier, 2012).

Recognizing that significant gaps exist in the understanding and management of ocean processes and trends, governments at the World Summit on Sustainable Development decided that a regular assessment of the oceans should be carried out (UNEP and IOC-UNESCO, 2009). The first Regular Process for Global Reporting and Assessment of the State of the Marine Environment, including Socioeconomic Aspects (known as the first World Ocean Assessment), approved by the United Nations General Assembly (see[1] for an overview of the process, its history and its outputs), reported that growing populations, economies and the agricultural and industrial requirements for feeding, clothing and housing the world's population are seriously degrading parts of the marine environment, especially near the coast (United Nations [UN], 2016). For example, widespread development of coastal regions has resulted in habitat loss, pollution and overfishing (United Nations [UN], 2016; Frid and Caswell, 2017; FAO, 2018). In some cases, the utilization of marine ecosystems by humans and associated impacts have reduced the marine environment's ability to provide the ecosystem goods and services we depend upon (Costanza et al., 2014; United Nations [UN], 2016). Further, activities on land and in river basins some distance from coastal zones have contributed to ocean pollution and coastal habitat degradation. The assessment concluded that without an integrated, coordinated, proactive, cross-sectoral and science-based approach to coastal and marine management, the resilience of coastal and marine ecosystems and their ability to provide vital services will continue to be reduced (United Nations [UN], 2016).

The second World Ocean Assessment (WOA) is currently being prepared for delivery in late 2020. Given that baselines for many aspects of marine socio-economic and bio-geo-physical systems were provided in the first assessment, a key focus for the second WOA is to build on these baselines and provide an assessment of changes that may have occurred since the first WOA. A number of emerging and important topics that were not covered specifically in the first WOA have also been included in the second WOA (e.g., anthropogenic noise, cumulative impacts, marine spatial planning, management approaches) in an effort to provide a comprehensive update to the first assessment across the Drivers-Pressures-State-Impacts-Response framework (Smeets and Weterings, 1999) utilized by the Regular Process.

Central to being able to provide comprehensive assessments of the marine environment are two components. First, is the utilization of ocean observations, monitoring outputs and the research required to temporally assess components of coastal and marine environments to establish their current state, impacts on them, responses that might be implemented and ongoing trends. Second, is the knowledge brokering of ocean observations and associated research to provide key information that can be utilized and applied to address management and policy needs at local, regional and global scales. Through identifying both knowledge gaps and capacity needs, assessments should also provide direction to policy makers for the future development and deployment of sustained observation systems required for supporting national aspirations associated with the sustainable development of coastal and marine ecosystems.

Here, we provide an overview of the vital information relating to ocean observations that supports the science policy interface developed and provided by the Regular Process. We detail the requirements for supporting the ongoing improvement and development of assessments conducted by the Regular Process, and for providing strategic linkages between the science community and end-users into the future. Finally, we detail the utility of the Regular Process in helping to guide planning for the activities of the United Nations (UN) Decade of Ocean Science for Sustainable Development[2].

[1] https://www.un.org/regularprocess/

[2] https://en.unesco.org/ocean-decade

ROLE OF OCEAN OBSERVATIONS IN THE WORLD OCEAN ASSESSMENT

Responding to changing and increasingly modified coastal and marine environments requires sufficient monitoring on relevant temporal and spatial scales, and an adaptive approach to management (Nicol et al., 2015; Constable et al., 2016). Adaptation of industries and activities to future environments and mitigation of possible impacts requires a capability to assess:

- the dynamics of coastal and marine ecosystems in response to variability in the marine environment over short, medium and longer time scales, including the key environmental drivers that influence the functional components of ecosystems;
- the responses of coastal and marine ecosystems to projected future changes to the Earth system and;
- the nature and extent of human activities occurring in coastal and marine environments and the sensitivity of coastal and marine ecosystems to singular and cumulative impacts of the activities interacting with them.

Central to the capability required for undertaking assessments of the marine environment and the impacts caused by human stressors is the collection of long time-series data from locations dispersed throughout the marine environment. This includes measurements of oceanography, biogeochemistry, marine soundscapes and species, communities and habitats, the varied means by which ocean resources are used and the cultural role that the ocean provides to human society (e.g., Nicol et al., 2012; Moore and Gulland, 2014; Addison et al., 2015; Erbe et al., 2015; Lynch et al., 2014; Evans et al., 2018). Also key to supporting the coordination of activities are data management systems that make such time series publicly available (e.g., the Ocean Biogeographical Information System (OBIS[3]) and systems for modeling and analyzing marine variables to support the investigation of future potential states, the interactions between marine activities and development of appropriate management strategies (e.g., Fulton et al., 2011; IPCC, 2014; Plagányi et al., 2014; Ortiz et al., 2016; Gattuso et al., 2018). Importantly, a capacity to then transform those sustained ocean observations into information that can support decision-making is needed.

The Regular Process provides an important pathway for the transformation of ocean observations into information that can be useful for decision makers at local, regional and global scales. It does this predominantly by tasking expert teams comprised of ocean scientists (across the fields of physics, chemistry, biology, socio-economics and humanities), managers, regulators and policy makers to synthesize published open access information to provide the state and trends of important environmental features and values over time, current use of the ocean environments and impacts created by that use. Further input to the process by the wider community is facilitated through regional workshops, a stakeholder dialogue and a peer review process. The finalized assessment is provided in two formats, the first a detailed summary of the current global state and the second a series of technical abstracts detailing topical domain areas that are specifically aimed at policy makers. The first WOA produced technical abstracts that were focused on findings relevant to climate change, biodiversity in areas beyond national jurisdiction and the UN Sustainable Development Goals (SDGs)[4].

Extensive work has been undertaken over the last couple of decades expand and better focus sustained observations of coastal and marine environments under formal frameworks at local, regional and global scales (e.g., Meredith et al., 2013; Lynch et al., 2014; Miloslavich et al., 2018a; POGO, 2018). In association, substantial work has been put into providing the supporting frameworks and mechanisms for providing access to those observations (e.g., Claustre et al., 2010; Proctor et al., 2010; Costello and Wieczorek, 2014). These efforts have contributed substantially to the capacity of those involved in the Regular Process to access datasets required for assessments included in the WOA. Further, the substantial progress in synthesizing observations at global scales into scientific understanding of ocean processes, (e.g., Dickey, 2003; Keeling et al., 2010; Chavez et al., 2011; Cheung et al., 2013; Harrison and Chiodi, 2015; Pecl et al., 2017) and activities (e.g., Halpern et al., 2008, 2017; OECD, 2016; FAO, 2018), particularly through modeling frameworks, has significantly supported the capacity of the Regular Process to provide a global perspective on the state of the ocean and the impacts of current activities. In addition, scientists and society have created an avenue for open dialogue with the emergence of citizen science[5]. In many regions, citizen science is providing support to scientific programs using technological advancements, state-of-the-art observation systems and analytical tools, as well as open sharing and exchange of information, further expanding ocean observations and understanding of ocean processes (e.g., Stocklmayer and Bryant, 2012; Trouille et al., 2019).

IMPROVEMENT AND DEVELOPMENT OF THE WORLD OCEAN ASSESSMENT

The number of components or processes that can be monitored in the marine environment, however, is endless, particularly when considering the ocean from a whole of system perspective (that is it's physical, chemical, biological, socio-economic and cultural elements). Despite significant progress in the establishment of ocean observation networks, associated capacity development and improved modeling and reporting processes, there are still fundamental gaps in observations and significant limitations in accessing comprehensive and timely ocean information. These continue to limit our understanding of ocean processes and activities across multiple spatial and temporal scales. Many of these gaps and limitations were detailed in the first WOA (see United Nations [UN], 2016) and similarly, these continue to be identified under other assessments across local, regional and

[3]http://www.iobis.org/

[4]https://www.un.org/regularprocess/content/technical-abstracts

[5]https://www.citizenscience.org/

global scales (e.g., BOBLME, 2014; UNEP-NAIROBI Convention and WIOMSA, 2015; IOC-UNESCO and UNEP, 2016; Ministry for the Environment and Statistics New Zealand, 2016; Evans et al., 2017).

Prioritizing what, when and how components of the marine ecosystem are monitored is essential if scientific data are to support marine managers in the changing and increasingly complicated environment they find themselves in. Initiatives such as the Framework of Ocean Observing (FOO; UNESCO, 2012) are assisting this prioritization process through three Global Ocean Observing System (GOOS) panels (the Climate and Physical Oceanography panel, the Biogeochemistry panel and the Biology and Ecosystems panel). These panels have been tasked with identifying a number of environment and ecosystem focused Essential Ocean Variables toward which global monitoring efforts should be focused over sustained time frames. This identification process has been based on the extent of societal importance of each variable and feasibility in implementation of observation. International observation networks, such as the International Quiet Ocean Experiment (Boyd et al., 2011) and Global Ocean Acidification Observing Network (Newton et al., 2015) are also developing frameworks for identifying variables for monitoring. Further, a number of targeted activities aimed at identifying environmental variables for various scientific and management purposes have been conducted globally (e.g., Cury and Christensen, 2005; Fabricius et al., 2012; Hayes et al., 2015). These networks and activities are specifying the methods associated with monitoring of variables, with the objectives of supporting assessments of the marine environment and informing management of the use of the marine environment. Continued development of these observation frameworks will provide ongoing opportunities for uptake into the assessments conducted under the Regular Process and in association, continued improvement of the WOA.

One of the main aims of the FOO is the international integration and coordination of interdisciplinary ocean observations. This is being facilitated through the streamlining of processes associated with the identification of societal demands, the collection of ocean observations, the analyses and assessment of those data and the sharing of information with policy makers, thereby building a pathway for the transfer of the knowledge created through observations to society. At present however, while great efforts have been placed into ocean observations and their analyses, including building global models from the integration of point sources of data, a clear protocol linking data outputs to policy development and implementation remains unidentified. By providing a clear avenue for delivery of ocean observations to policy makers, the WOA can play a role to assist with this key knowledge brokering component of the FOOs aims: data to information for policy needs. Strengthening the communication links and opportunities for input into the Regular Process would serve to ensure that these pathways are identified and established. One potential avenue for facilitating a strengthening of communication links and opportunities is through UN Oceans[6], an inter-agency mechanism that aims to strengthen and promote coordination and coherence of UN system activities related to ocean and coastal areas. Embedding the Regular Process as a mechanism for linking data outputs to policy development and implementation within UN Oceans would assist in achieving the FOOs aims, whilst also ensuring that data inputs into the assessment process are maximized.

Most observation networks however, do not extend into economic, social and cultural aspects of the ocean and as a consequence, focused, sustained and publically accessible observations of these aspects of marine systems in standardized formats at regional and global scales are lacking (noting that some socio-economic indicators have been developed for specific locations and management purposes – see for example Rey-Valette et al., 2005; Foley et al., 2014). One area in which there are exceptions is fisheries and aquaculture, where regular reporting of some aspects of the socio-economics of these activities occurs at regional and global scales (e.g., FAO, 2018). Compiling economic, social and cultural information into useable formats for inclusion within an assessment framework (including extracting ocean based components from overall reporting across terrestrial and marine systems) for synthesizing at global scales requires considerable effort, often beyond the ability of those individuals or groups of individuals involved in contributing to assessments under the Regular Process. This is a clear area where extension of current observation frameworks to incorporate sustained and standardized monitoring of economic, social and cultural aspects of the ocean would significantly improve assessments undertaken under the Regular Process. There is an aim for variables being developed under the Biology and Ecosystems panel to extend to pressures placed on marine ecosystems by human activities (in the first instance this might include ocean noise and marine debris including plastics). The outputs from the Regular Process could assist in guiding the process for identifying such variables, and in doing so, can provide a pathway for further improvements to the observations contributing to the WOA.

For the second WOA, the Regular Process has expanded opportunities for the exchange of information and input into the assessment by incorporating two rounds of regional workshops, held in 2017 and 2018, and a stakeholder dialogue and capacity building event held in 2019 (see[7] for outputs from the workshops and[8] for outputs from the stakeholder dialogue and capacity building event). These meetings have provided platforms for widespread regional input into the process by science, management and policy communities and facilitated increased awareness of activities and outputs of relevance across ocean regions. In particular, the workshops and dialogue event have highlighted the challenges associated with contributing to the assessments of the Regular Process within ocean regions, particularly in resourcing contributors and the coordination of local and regional inputs to the process for synthesis at the global level. Highlighting these challenges has provided

[6]http://www.unoceans.org/

[7]https://www.un.org/regularprocess/content/second-round-regional-workshops

[8]https://www.un.org/regularprocess/content/multi-stakeholders

clear guidance to the Regular Process on current gaps in ocean observations used to support assessments and where action is needed to develop global capacity for supporting the collection, analyses and interpretation ocean observations (summarized in the first WOA – see United Nations [UN], 2016). This adds to assessments of current capacity gaps in ocean observations and associated ocean science provided in the Global Ocean Science Report (UNESCO, 2017) and detailed in numerous publications (e.g., see Koslow and Couture, 2015; Buch et al., 2017; Bax et al., 2018; Ludwigsen et al., 2018; Miloslavich et al., 2018b; POGO, 2018).

Developing the knowledge to fill current gaps in ocean observations and the science supporting the assessment is an ongoing challenge. It will require coordinated efforts to identify and develop the capacity to meet scientific, technological, and communication needs across spatial and temporal scales relevant for assessment and sustainable management of the marine environment (United Nations [UN], 2016). It will also require current calls to support pathways for capacity building to be recognized and met by individual countries and their scientific, education and management agencies. The development of scientific, technological and communication capacity required to support sustainable marine management and processes such as the WOA, GOOS, the UN SDGs and others will require long-term, sustained partnerships, built on mutual commitment, trust and investment.

Achieving widespread understanding of the need and commitment to long-term, sustained partnerships that support capacity and capability building requires that all aspects of society has a clear understanding of the value of the services provided by the ocean, current impacts on those services and the strategies required to achieve a sustainable future. It is recognized that the science community needs to move beyond the collection of data and publication of their research results in peer literature, formats that are not easy to "digest" by most of society. Further, strengthening of the pathways for transformation of ocean observations into information that can be understandable and therefore useful for decision makers at multiple spatial scales, should consider how best to communicate the outputs of assessments to society.

Programs focused on developing frameworks for improving ocean literacy provide an avenue for formal and informal educators to engage and educate society on ocean system issues (see UNESCO, 2005; National Geographic Society [NGS] et al., 2005; Dupont and Fauville, 2017). These frameworks for ocean literacy serve as a platform for inspiring people in ocean research and beyond (Bray et al., 2012; Trouille et al., 2019). When particularly targeted at younger age groups, this promotes an increased understanding by those that will contribute to the next generation of scientists, managers, policy makers, and those involved in business and industry. This therefore provides the opportunity for facilitating a step change in the way in which the ocean is valued and used. Many initiatives have been launched in order to increase societal awareness of the ocean and ocean ecosystems. These include government led initiatives such as the European Commission programs and projects Sea for Society[9], Sea Change[10] and MARINA[11], and those led by non-governmental organizations such as the Ocean Sanctuary Alliance[12], World Ocean Network[13] and World Ocean Observatory[14]. Business associations focused on identifying and implementing sustainable practices and guiding future investment such as the UN Global Compact[15], particularly through the Action Platform for Sustainable Ocean Business and the World Ocean Council[16] also provide the opportunity for the development of direct communication pathways and avenues for engagement to better inform and engage society on ocean system issues identified by the Regular Process.

STRATEGIC LINKAGES TO THE UNITED NATIONS DECADE OF OCEAN SCIENCE FOR SUSTAINABLE DEVELOPMENT

The United Nations' General Assembly (UN-GA) decided that the Regular Process should not undertake any policy analysis or make any recommendations on policy or management. By approving the Summary of the Assessment however, the UN-GA, representing the world's governments, has indicated that it accepts that the gaps in knowledge and capacity identified in the first WOA exist. Identifying a prioritization process for filling knowledge gaps and building capacity is an urgent task and one that the global community could be tasked with under the UN Decade of Ocean Science for Sustainable Development (the Decade) as a useful step in progressing the collection, analyses and interpretation of ocean observations.

Key to ensuring the uptake and utilization of the WOA in bridging science with policy will be the establishment of strategic linkages that not only provide pathways for access to and utilization of datasets for conducting analyses at global scales, but also provide for the establishment of networks amongst science, management and policy communities. Development of linkages and networks is critical for ensuring that key science-based information on marine systems can be accessed in useful formats by policy makers for future sustainable use of the marine environment. They are also key for ensuring that the resources required for supporting national aspirations associated with the sustainable development of coastal and marine ecosystems, including the sustained observation systems, are identified and implemented.

Just as the Census of Marine Life (see Williams et al., 2010), provided an opportunity to bring researchers together to facilitate

[9]http://seaforsociety.eu
[10]http://www.seachangeproject.eu/
[11]https://www.marinaproject.eu/
[12]https://www.oceansanctuaryalliance.org
[13]https://www.worldoceannetwork.org
[14]http://worldoceanobservatory.org
[15]https://www.unglobalcompact.org/
[16]https://www.oceancouncil.org/

a step change in our understanding of the world's marine biodiversity, the Decade provides an opportunity to progress the development of a science policy interface for sustainable use of the global ocean. Implementation of infrastructure that supports the transfer of observations of the physical, biogeochemical, ecological, economic, social and cultural components of the oceans into planning and policy development formats will increase the likelihood that scientific evidence will be used in policy and management decision making. This will have the overall effect of increasing the success of those decisions in meeting their objectives, particularly in relation to the sustainable development of ocean resource and conservation of ecosystem services.

Planning for the Decade is underway with an initial roadmap developed to help guide the planning process (available at[17]). This document explicitly identifies the role the first WOA has had in identifying changes and losses in the structure, function and benefits obtained from marine systems and that action is clearly required in addressing these declines and losses. It also clearly articulates the role the Decade can have in significantly contributing to the understanding of ocean processes and activities and the way we manage cooperation and partnerships in support of sustainable development and a healthy ocean. Further, it details that the Decade should aim to address identified knowledge gaps and strengthen the conduct of the WOA, thereby identifying the potential improvements the Decade can provide to assessments under the Regular Process. Establishment of clear linkages between the Decade and the Regular Process, particularly during the planning process will ensure that these aims are achieved and future ongoing improvement of the WOA is facilitated.

[17] https://en.unesco.org/ocean-decade/resources

CONCLUSION

By providing a global perspective on the current state of the marine environment, its use and impacts affecting its functioning, the WOA provides a key link for facilitating knowledge transfer across the science-policy interface for decision making on ocean issues. In providing this link, the WOA plays an essential role in assisting initiatives such as the FOO in achieving their aims. Strengthening of the knowledge brokering role of the WOA and in particular, addressing knowledge gaps will rely on building communication links and opportunities for input into the Regular Process. It will also rely on developing the capacity to meet scientific, technological, and communication needs across spatial and temporal scales relevant for the assessment. The UN Decade of Ocean Science for Sustainable Development provides an opportunity to progress the capacity development needed and strengthen the science policy interface required for sustainable use of the global ocean. Establishment of clear linkages between the Regular Process, the Decade and initiatives such as FOO will facilitate the enhanced understanding of ocean processes, activities and decision making required to support sustainable development, whilst maintaining a healthy ocean into the future.

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REFERENCES

Addison, P. F. E., Flander, L. B., and Cook, C. N. (2015). Are we missing the boat? Current uses of long-term biological monitoring data in the evaluation and management of marine protected areas. *J. Environ. Manag.* 149, 148–156. doi: 10.1016/j.jenvman.2014.10.023

Barbier, E. B. (2012). Progress and challenges in valuing coastal and marine ecosystem services. *Rev. Environ. Econ. Pol.* 6, 1–19. doi: 10.1093/reep/rer017

Barbier, E. B. (2017). Marine ecosystem services. *Curr. Biol.* 27, R431–R510.

Bax, N. J., Appeltans, W., Brainard, R., Duffy, J. E., Dunstan, P., Hanich, Q., et al. (2018). Linking capacity development to GOOS monitoring networks to achieve sustained ocean observing. *Front. Mar. Sci.* 5:346. doi: 10.3389/fmars.2018.00346

BOBLME (2014). *Assessing, Demonstrating and Capturing the Economic Value of Marine & Coastal Ecosystem Services in The Bay of Bengal Large Marine Ecosystem*. Phuket: BOBLME.

Boyd, I. L., Frisk, G., Urban, E., Tyack, P., Ausubel, J., Seeyave, S., et al. (2011). An international quiet ocean experiment. *Oceanography* 24, 174–181. doi: 10.5670/oceanog.2011.37

Bray, B., France, B., and Gilbert, J. K. (2012). Identifying the essential elements of effective science communication: what do the experts say? *Int. J. Sci. Educ. B* 2, 23–41. doi: 10.1080/21548455.2011.611627

Buch, E., Palacz, A., Karstensen, J., Fernandez, V., Dickey-Collas, M., and Borges, D. (2017). *Capacities and Gap Analysis*. Kiel: GEOMAR Helmholtz Centre for Ocean Research Kiel, 105.

Chavez, F. P., Messié, M., and Pennington, J. T. (2011). Marine primary production in relation to climate variability and change. *Annu. Rev. Mar. Sci.* 3, 227–260. doi: 10.1146/annurev.marine.010908.163917

Cheung, W. W. L., Watson, R., and Pauly, D. (2013). Signature of ocean warming in global fisheries catch. *Nature* 497, 365–368. doi: 10.1038/nature12156

Claustre, H., Antoine, D., Boehme, L., Boss, E., D'Ortenzio, F., D'Andon, O. F., et al. (2010). "Guidelines towards an integrated ocean observation system for ecosystems and biogeochemical cycles," in *Proceedings of the OceanObs'09: Sustained Ocean Observations and Information for Society*, Vol. 1, eds J. Hall, D. E. Harrison, and D. Stammer (Venice: ESA Publication).

Constable, A. J., Costa, D. P., Schofield, O., Newman, L., Urban, E. R., Fulton, E. A., et al. (2016). Developing priority variables ("ecosystem essential ocean variables" – eEOVs) for observing dynamics and change in southern ocean ecosystems. *J. Mar. Sys.* 161, 26–41. doi: 10.1016/j.jmarsys.2016.05.003

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., et al. (1997). The value of the world's ecosystem services and natural capital. *Nature* 387, 253–260. doi: 10.1126/sciadv.1601880

Costanza, R., Groot, R., Sutton, P., van der Ploeg, S., Anderson, S. J., Kubiszewski, I., et al. (2014). Changes in the global value of ecosystem services. *Glob. Environ. Change* 26, 152–158. doi: 10.1016/j.gloenvcha.2014.04.002

Costello, M. J., and Wieczorek, J. (2014). Best practice for biodiversity data management and publication. *Biol. Cons.* 173, 68–73. doi: 10.1016/j.biocon.2013.10.018

Covich, A. P., Austen, M. C., BÄRlocher, F., Chauvet, E., Cardinale, B. J., Biles, C. L., et al. (2004). The role of biodiversity in the functioning of freshwater and marine benthic ecosystems. *BioScience* 54, 767–775.

Cury, P. M., and Christensen, V. (2005). Quantitative ecosystem indicators for fisheries management – introduction. *ICES J. Mar. Sci.* 62, 307–310. doi: 10.1016/j.icesjms.2005.02.003

Dickey, T. D. (2003). Emerging ocean observations for interdisciplinary data assimilation systems. *J. Mar. Syst.* 4, 5–48. doi: 10.1016/s0924-7963(03)00011-3

Duke, N. C., Meynecke, J. O., Dittmann, S., Ellison, A. M., Anger, K., Berger, U., et al. (2007). A world without mangroves? *Science* 317, 41–42. doi: 10.1126/science.317.5834.41b

Dupont, S., and Fauville, G. (2017). "Ocean literacy as a key toward sustainable development and ocean governance," in *Handbook on the Economics and Management of Sustainable Oceans*, ed. A. Markandya (Cheltenham: Edward Elgar Publishers), 519–537. doi: 10.4337/9781786430724.00037

Erbe, C., Verma, A., McCauley, R., Gavrilov, A., and Parnum, I. (2015). The marine soundscape of the Perth Canyon. *Prog. Oceanogr.* 137, 38–51. doi: 10.1016/j.pocean.2015.05.015

Evans, K., Bax, N., and Smith, D. C. (2017). *Australia State of the Environment 2016: Marine Environment, Independent Report to the Australian Government Minister for the Environment and Energy*. Canberra: Australian Government Department of the Environment and Energy.

Evans, K., Bax, N., and Smith, D. C. (2018). Enhancing the robustness of a national assessment of the marine environment. *Mar. Pol.* 98, 133–145. doi: 10.1016/j.marpol.2018.08.011

Fabricius, K. E., Cooper, T. F., Humphrey, C., Uthicke, S., De'ath, G., Davidson, J., et al. (2012). A bioindicator system for water quality on inshore coral reefs of the Great Barrier Reef. *Mar. Poll. Bull.* 65, 320–332. doi: 10.1016/j.marpolbul.2011.09.004

FAO (2018). "The state of world fisheries and aquaculture 2018," in *Proceedings of the Meeting the Sustainable Development Goals*, Rome.

Foley, N. S., Corless, R., Escapa, M., Fahy, F., Fernandez-Macho, J., Gabriel, S., et al. (2014). Developing a comparative marine socio-economic framework for the European Atlantic area. *J. Ocean Coast. Econ.* 1:3. doi: 10.15351/2373-8456.1007

Frid, C. L. J., and Caswell, B. A. (2017). *Marine Pollution*. Oxford: Oxford University Press.

Fulton, E. A., Link, J. S., Kaplan, I. C., Savina-Rolland, M., Johnson, P., Ainsworth, C., et al. (2011). Lessons in modelling and management of marine ecosystems: the Atlantis experience. *Fish Fish.* 12, 171–188. doi: 10.1111/j.1467-2979.2011.00412.x

Gattuso, J.-P., Magnan, A. K., Bopp, L., Cheung, W. W. L., Duarte, C. M., Hinkel, J., et al. (2018). Ocean solutions to address climate change and its effects on marine ecosystems. *Front. Mar. Sci.* 5:337. doi: 10.3389/fmars.2018.00337

Hall, S. J., Hilborn, R., Andrew, N. L., and Allison, E. H. (2013). Innovations in capture fisheries are an imperative for nutrition security in the developing world. *PNAS* 110, 8393–8398. doi: 10.1073/pnas.1208067110

Halpern, B. S., Frazier, M., Afflerbach, J., O'Hara, C., Katona, S., Stewart Lowndes, J. S., et al. (2017). Drivers and implications of change in global ocean health over the past five years. *PLoS One* 12:e0178267. doi: 10.1371/journal.pone.0178267

Halpern, B. S., Walbridge, S., Selkoe, K. A., Kappel, C. V., Micheli, F., D'Agrosa, C., et al. (2008). A global map of human impact on marine ecosystems. *Science* 319, 948–952. doi: 10.1126/science.1149345

Harrison, D. E., and Chiodi, A. M. (2015). Multi-decadal variability and trends in the El niño-southern oscillation and tropical pacific fisheries implications. *Deep Sea Res. II* 113, 9–21. doi: 10.1016/j.dsr2.2013.12.020

Hayes, K. R., Dambacher, J. M., Hedge, P. T., Watts, D., Foster, S. D., Thompson, P. A., et al. (2015). *Towards a Blueprint for Monitoring Key Ecological Features in the Commonwealth Marine Area*. Hobart, TAS: NERP Marine Biodiversity Hub.

IOC-UNESCO, and UNEP (2016). *Open Ocean: Status and Trends, Summary for Policy Makers*. Nairobi: United Nations Environment Programme (UNEP).

IPCC (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva: IPCC, 151.

Keeling, R. F., Körtzinger, A., and Gruber, N. (2010). Ocean deoxygenation in a warming world. *Annu. Rev. Mar. Sci.* 2, 199–229. doi: 10.1146/annurev.marine.010908.163855

Koslow, J. A., and Couture, J. (2015). Pacific Ocean observation programs: gaps in ecological time series. *Mar. Pol.* 58, 408–414. doi: 10.1016/j.marpol.2014.09.003

Ludwigsen, C. A., Pirazzini, R., Sagen, H., Hamre, T., Sandven, S., Stette, M., et al. (2018). *Report on Present Observing Capacities and Gaps: Ocean and Sea Ice Observing System*. Norway: Nansen Environmental and Remote Sensing Center.

Lynch, T. P., Morello, E. B., Evans, K., Richardson, A. J., Rochester, W., Steinberg, C. R., et al. (2014). IMOS national reference stations: a continental-wide physical, chemical and biological coastal observing system. *PLoS One* 19:e113652. doi: 10.1371/journal.pone.0113652

Meredith, M. P., Schofield, O., Newman, L., Urban, E., and Sparrow, M. (2013). The vision for a southern ocean observing system. *Environ. Sustain.* 5, 306–313. doi: 10.1016/j.cosust.2013.03.002

Miloslavich, P., Bax, N. J., Simmons, S. E., Klein, E., Appeltans, W., Aburto-Oropeza, O., et al. (2018a). Essential ocean variables for global sustained observations of biodiversity and ecosystem changes. *Glob. Change Biol.* 2018, 2416–2433. doi: 10.1111/gcb.14108

Miloslavich, P., Seeyave, S., Muller-Karger, F., Bax, N., Ali, E., Delgado, C., et al. (2018b). Challenges for global ocean observation: the need for increased human capacity. *J. Oper. Oceanogr.* 1–20. doi: 10.1080/1755876X.2018.1526463

Ministry for the Environment and Statistics New Zealand (2016). *New Zealand's Environmental Reporting Series: Our Marine environment 2016*. Available at: http://www.mfe.govt.nz/publications/marine-environmental-reporting/our-marine-environment-2016 (accessed June 27, 2016).

Moore, S. E., and Gulland, F. M. D. (2014). Linking marine mammal and ocean health in the "new normal" arctic. *Ocean Coast. Manage* 102, 55–57. doi: 10.1016/j.ocecoaman.2014.08.011

National Geographic Society [NGS], National Oceanic, Atmospheric Administration, Centers for Ocean Sciences Education Excellence, National Marine Educators Association, and College of Exploration. (2005). *Ocean Literacy: The Essential Principles of Ocean Sciences K-12*. Silver Spring, MD: NOAA.

Newton, J. A., Feely, R. A., Jewett, E. B., Williamson, P., and Mathis, J. (2015). *Global Ocean Acidification Observing Network: Requirements and Governance Plan*. Available at: www.goa-on.org/docs/GOA-ON_plan_print.pdf (accessed June 27, 2016).

Nicol, S., Fuller, R. A., Iwamura, T., and Chadès, I. (2015). Adapting environmental management to uncertain but inevitable change. *Proc. R. Soc. B* 282:20142984. doi: 10.1098/rspb.2014.2984

Nicol, S. J., Allain, V., Pilling, G. M., Polovina, J., Coll, M., Bell, J., et al. (2012). An ocean observation system for monitoring the effects of climate change on the ecology and sustainability of pelagic fisheries in the Pacific Ocean. *Clim. Change* 119:131. doi: 10.1007/s10584-012-0598-y

OECD (2016). *OECD Factbook 2015-2016: Economic, Environmental and Social Statistics*. Paris: OECD Publishing.

Ortiz, I., Aydin, K., Hermann, A. J., Gibson, G. A., Punt, A. E., Wiese, F. K., et al. (2016). Climate to fish: Synthesizing field work, data and models in a 39-year retrospective analysis of seasonal processes on the eastern bering sea shelf and slope. *Deep Sea Res. II* 134, 390–412. doi: 10.1016/j.dsr2.2016.07.009

Palumbi, S. R., Sandifer, P. A., Allan, J. D., Beck, M. W., Fautin, D. G., Fogarty, M. J., et al. (2009). Managing for ocean biodiversity to sustain marine ecosystem services. *Front. Ecol. Environ.* 7:204–211. doi: 10.1890/070135

Pecl, G. T., Araújo, M. B., Bell, J. D., Blanchard, J., Bonebrake, T., Ching Chen, I.-C., et al. (2017). Biodiversity redistribution under climate change: impacts on ecosystems and human well-being. *Science* 355:1389. doi: 10.1126/science.aai9214

Plagányi, E. E., Ellis, N., Blamey, L. K., Morello, E. B., Norman-Lopez, A., Robinson, W., et al. (2014). Ecosystem modelling provides clues to understanding ecological tipping points. *Mar. Ecol. Prog. Ser.* 512, 99–113. doi: 10.3354/meps10909

POGO (2018). *The value of the Global Ocean Observing System and the Regular Assessment of the State of the Ocean in Support of Wise Decision-Making. A Statement by the Partnership for Observation of the Global Ocean (POGO)*. Plymouth: Partnership for Observation of the Global Ocean.

Proctor, R., Roberts, K., and Ward, B. J. (2010). A data delivery system for IMOS, the australian integrated marine observing system. *Adv. Geosci.* 28, 11–16. doi: 10.5194/adgeo-28-11-2010

Rey-Valette, H., Bodiguel, C., Cunningham, S., Degnbol, P., Hegland, T. J., Sverdrup-Jensen, S., et al. (2005). *INDECO:Review of the Usage of Socio-Economic Indicators on the Environmental Impact of Fishing Activities*. London: IEEP.

Smeets, E., and Weterings, R. (1999). *Environmental Indicators: Typology and Overview*. Report No. 25, European Environment Agency, Copenhagen.

Stocklmayer, S. M., and Bryant, C. (2012). Science and the public—What should people know? *Int. J. Sci. Educ. B* 2, 81–101. doi: 10.1080/09500693.2010.543186

Trouille, L., Lintott, C. J., and Fortson, L. F. (2019). Citizen science frontiers: efficiency, engagement, and serendipitous discovery with human–machine systems. *PNAS* 116, 1902–1909. doi: 10.1073/pnas.1807190116

UNEP, and IOC-UNESCO (2009). *An Assessment of Assessments, Findings of the Group of Experts. Start-up phase of a Regular Process for Global Reporting and Assessment of the State of the Marine Environment including Socio-economic Aspects*. Nairobi: UNEP.

UNEP-NAIROBI Convention, and WIOMSA (2015). *The Regional State of the Coast Report: Western Indian Ocean*. Nairobi: UNEP.

UNESCO (2005). *Aspects of Literacy Assessment: Topics and ISSUES from the UNESCO Expert Meeting*. Paris: United Nations of Education Scientific and Cultural Organisation.

UNESCO (2012). *A framework for Ocean Observing. By the Task Team for an Integrated Framework for Sustained Ocean Observing*. Paris: United Nations of Education Scientific and Cultural Organisation.

UNESCO (2017). *Global Ocean Science Report—The current Status of Ocean Science Around the world*. Paris: UNESCO Publishing.

United Nations [UN] (2016). *The First Global Integrated Marine Assessment. World Ocean Assessment I*. Cambridge: Cambridge University Press.

Williams, M. J., Ausubel, J., Poiner, I., Garcia, S. M., Baker, D. J., Clark, M. R., et al. (2010). Making marine life count: a new baseline for policy. *PLoS Biol.* 8:e1000531. doi: 10.1371/journal.pbio.1000531

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Search and Rescue Applications: On the Need to Improve Ocean Observing Data Systems in Offshore or Remote Locations

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Search and rescue (SAR) in remote maritime locations is a difficult mission. One of the limitations in these isolated regions is the low density of available oceanographic data for model validation. In order to examine the state of remote search and rescue a review of maritime search theory and advances was conducted. This included basic drift theory, leeway, available environmental data, and the current methods used by the United States Coast Guard for SAR operations. In particular the U.S. Coast Guard's fourteenth district's SAR case history was examined and it was found that 60% of SAR cases fall outside of areas that have high-resolution wind and current data, with only global scale model forecasts available. In addition, 2% of cases occurred in offshore waters (> 12 *nm* from land) and exceeded 36 h in asset response time. Three SAR simulations were run off the coast of Oahu, Hawaii using the same wind data but different surface current models. These simulations had extremely large (up to 12,000 km^2) search areas, highlighting the need for solutions that narrow these expected areas.

Keywords: search and rescue, ocean currents, drift, leeway, remote regions

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1. INTRODUCTION

The United States Coast Guard (USCG) is responsible for more than 21.3 million square nautical miles of ocean and oversees 11 mission areas including aids to navigation, living marine resources, law enforcement, and search and rescue. In 2017, the USCG responded to 16,000 search and rescue (SAR) cases and saved over 4,000 lives. Although most SAR cases are short lived and do not require an extensive search, the cases that do extend over multiple days and necessitate extensive asset allocations are quite expensive. These cases generally have a low probability of successfully finding missing persons alive. During a typical SAR case, nowcast and forecasted oceanographic and meteorological data from numerical models are used to predict the drift pattern of the lost object or person using leeway calculations. In many areas there are limited observational oceanographic datasets available to verify drift prediction from the fields, which can reduce the probability of success. A prime example is the Coast Guard's fourteenth district, which is responsible for the Hawaiian Islands, America Samoa, Guam, the Northern Mariana Islands, and the Republic of the Marshall Islands as well as the high seas in between. Many of these regions are isolated and lack observational current data for model validation. In addition, the island regime creates unique issues that are not common in mainland region cases such as the large ocean distance between population centers, crossing between islands can cover deep, exposed waters and may be done in small craft (Brushett et al., 2014). Here, we review the literature on SAR in maritime environments and examine SAR statistics in the USCG's fourteenth district to identify gaps in our current oceanographic data coverage. Then, using current methods and datasets available to USCG SAR, we run three example case studies in the Hawaiian Islands.

2. SEARCH AND RESCUE FUNDAMENTALS

Objects lost at sea are subject to forcing from ocean currents, winds and waves. For SAR purposes, an object drifting in the ocean subject only to a current V_c is expected to drift at the same speed as and in the direction of V_c. However, the addition of wind complicates the equations. Due to the complex nature of wind forcing on the ocean surface and the fact that the area exposed to the wind is different for each search object, a drift prediction requires more than just knowledge of the surface current speed. Total drift is predicted from leeway, defined as *the motion of the object induced by the 10-m reference height wind and surface waves relative to the ocean current* in Breivik et al. (2013) as well as Allen and Plourde (1999). Using the definitions put forth in Allen (2005), wind forcing is treated as a vector with a direction and magnitude. Leeway speed is the velocity given to a drifting object from the wind, relative to the ambient currents. It is usually noted as a percentage of the wind speed. Leeway angle represents the angular offset from the downwind direction. This angle, when combined with the downwind component leeway, and the crosswind component, creates the full leeway vector. A thorough discussion of these principles is given in many previous key publications (Allen, 2005; Hackett et al., 2006; Breivik and Allen, 2008; Breivik et al., 2013).

The leeway of an object does not just represent wind forcing on a drifting object. As detailed in Brushett et al. (2014) and Hodgins and Hodgins (1998), the total drift of an object is the sum of the drift caused by the currents and the drift caused by leeway. However, inside both of these sources of drift are subcategories. The drift caused by currents can be thought of as the superposition of the drift caused by surface currents and the drift caused by stokes drift. The drift caused by leeway can similarly be broken down into a component caused by wind upon the surface of the ocean and the impact of waves. Leeway estimates therefore include impacts from stokes drift, waves, and wind. It has been shown by Hodgins and Hodgins (1998) and Breivik and Allen (2008) that leeway impacts caused by wave motion can be ignored for objects smaller than one half of the wavelength of the average wave. The leeway caused by the stokes drift from local wind driven sea waves will predominantly be in the downwind direction. Leeway caused by stokes drift from swell could occur in any direction and would therefore be wrapped into both the downwind and crosswind leeway estimates.

Leeway is normally calculated using either the direct method, by measuring drift through water using attached current meters and anemometers, or the indirect method of subtracting the estimate of current drift from the total drift (Allen and Plourde, 1999). For different drift objects such as a person in the water, a liferaft, or a 36′ sailboat, leeway parameters specific to each object need to be measured and recorded for use during SAR operations. As of this publication date there are 89 different leeway categories available, with more being tested every year. New advancements in leeway calculation have shown that it is possible to create a model of leeway drift using the balance of hydrodynamic and aerodynamic forces. This was conducted by Di Maio et al. (2016) on a person in the water, with the modeled leeway performing better than the statistical approach described above. If this model proves accurate with other objects, it could reduce the need for direct measurement of leeway parameters.

3. OCEANOGRAPHIC DATA

Observational data can be used during search and rescue operations in three main ways: (a) validation of numerical model output, (b) used directly or through a short term predictive model to predict drift, or (c) through assimilation into ocean models that are then used to predict drift.

3.1. Surface Drifting Buoys

Surface drifting buoys are commonly used to validate ocean currents during SAR operations (Breivik et al., 2013). These units are deployed in the area of interest and their drift is compared to available numerical model outputs, which aide in the placement of search patterns used by response assets. A thorough discussion of the use of surface drifting buoys for SAR is provided in Berkson et al. (2019), Wilkin et al. (2017), Roarty et al. (2018), and Roarty et al. (2016).

3.2. High Frequency Radar

The availability of High Frequency (HF) Radar surface current data has expanded over the last twenty years. Integrated HF radar networks are available for operational oceanographic use in the United States (IOOS, discussed below), Australia (Australian Coastal Ocean Radar Network, ACORN), the Mediterranean Sea (Tracking Oil Spill and Coastal Awareness, TOSCA) and since 2017, as a global HF radar network (http://global-hfradar.org/). The U.S. Integrated Ocean Observing System (IOOS), through its academic and state partners, is one of the main providers of HF radar data for SAR operations (Harlan et al., 2011) in the United States. Work by Bellomo et al. (2015) showed that the use of HF radar data in SAR and oil tracking operations reduced position error and search range by up to a factor of 5. In addition to the real-time surface currents which can be used for model validation, in some regions the data is used to produce forecast fields from a program called the Short Term Predictive System (STPS) (Harlan et al., 2011). As discussed by Ullman et al. (2003), the STPS, developed and run by the University of Connecticut with support from US IOOS, predicts the surface currents up to 25 h in advance by breaking them down into two components: a tidal-driven flow and a non-tidal driven flow (2003). The tidal driven flow is predicted using harmonic analysis of 1 month of HF radar data and the non-tidal flow is predicted using Gauss-Markov estimation (Ullman et al., 2003). This STPS is presently available for SAR use for the entire West Coast where there is HF radar coverage and on the East Coast in the Mid-Atlantic region. However, this is not the only STPS available. Two complementary studies used different modeling methods for STPS from HF radar data, one using a long historical record of HF radar currents to train the model and the second was developed as STPS for rapid deployment. Frolov et al. (2012) developed a predictive algorithm for surface currents up to 48 h in the future by using empirical orthogonal functions (EOFs). They used 1–2 years (minimum) of previous HF radar data and deconstructed it using EOFs to capture spatial variability which they then used to train their model. Their EOF-based STPS was more accurate for their area of interest than other existing operational model forecasts. In contrast, Barrick et al. (2012) developed a STPS for rapid deployment of HF radars in cases where radars are deployed for emergency operations, such as oil spill response. In this case, 1–2 years of HF radar data was not available to initiate a short-term predictive model. Instead, they created a STPS algorithm that could work with as little as 12 h of previous data with predictions 24 h into the future. They did experience poor performance during short-term local wind events, but the majority of the predictions agreed with actual drift where mean winds were used. Where available, these STPS programs provide a spatially robust data set of predicted ocean currents for emergency responders.

3.3. Data Assimilating Ocean Current Models

The purpose of data assimilation into numerical models is to move beyond a purely mathematical solution to one that resembles reality as closely as possible. Le Traon (2013) outlines three major advancements in oceanography: satellite altimetry, Argo, and operational oceanography, but the three advancements are not independent, instead they work hand in hand to improve our knowledge of ocean science. Satellite altimetry provides global high resolution, near-real time sea surface heights. Oke and Schiller (2007) found that for the Ocean Forecasting Australia Model (OFAM) altimetry was critical in order to represent mesoscale variability, but without Argo measurements salinity variations were not well resolved. This was reinforced by Le Traon (2013), who showed that ocean models rely on altimetry and Argo data sets to constrain the models. Using data assimilation, improvements were also noted in the Forecast Ocean Assimilation Model (FOAM) in the North Atlantic and Nucleus for European Modeling of Ocean VARiational (NEMOVAR) global output (Cummings et al., 2009). However, data assimilation into models can be a computationally intense processes that requires dedicated supercomputers. In addition, not all observations are available in real time and most observational data runs through at least a preliminary quality control process before assimilation into a model (Martin et al., 2015).

3.4. Search Models

To run drift simulations, the USCG uses the Search and Rescue Optimal Planning System (SAROPS) computer program. This program represents a large improvement in SAR technology and methods, from previous versions or hand calculations. For reference, Frost and Stone (2001) and Breivik et al. (2013) provide a robust overview of search methods prior to the implementation of SAROPS in the early 2000s. SAROPS is computationally similar to SAR models used in the East and South China Seas (Cho et al., 2014) and the Australian SARMAP program (http://asascience.com/software/sarmap/). SAROPS subjects drift objects to an ambient current with the specific leeway coefficients input for each search object given the observed or modeled wind speed and direction. It then uses a Monte Carlo approach to forecast drift position from a variety of initial condition scenarios that reflect the information from the reporting sources. The initial conditions include one to four search objects, uncertainty in time and spatial distributions. The spatial distributions include: (1) bi-variate normal distribution about point from a Last-Known-Position, (2) uniform distribution over a regular polygon for simulating fishing grounds, (3) distributions from lines of position(s) from radio transmissions or flare sightings, and (4) simulated voyages of the originating craft. Each object's position is subject to random walks to account for noise in the wind and current fields at the location of the particles, where each subsequent application of the random walk is correlated to the one before. One simulation can be run with up to 10,000 particles (representing 10,000 different drift runs for each object) per initial scenario. The output is then a probability map showing where the object is most likely to be found at each time-step, based on location of the highest particle density at that point in the simulation and accounting for all previous search efforts and the subjective weighting of the scenarios and 1–4 search objects likelihood. In order to complete these calculations, SAROPS requires access to oceanographic and meteorological data. This data is pulled from the Environmental Data Server (EDS) that aggregates and stores observational and forecasted wind and currents. This data includes global and regional numerical model forecasts of ocean currents and winds. It also includes inputs of observational data from High Frequency (HF) Radars and Self-Locating Datum Marker Buoys (SLMDBs), a code-style drifter deployed during a SAR case to validate model currents. Both West and East Coast STPS current fields are provided to the EDS for use by SAROPS.

4. SEARCHES IN OFFSHORE AND REMOTE LOCATIONS

What makes remote search and rescue different from mainland scenarios is the low density of oceanographic data and the distance from response assets. Outside of the near-shore waters, many valuable resources are unavailable and due to the travel distance for response assets, time available to search on scene is reduced. In addition, responders have to take into account fuel costs and crew fatigue constraints. The Central Pacific SAR area of responsibility, and the Hawaiian Islands in particular, make a good case study for remote SAR. The Hawaiian Islands are isolated and have a low ratio of land to water (the islands only make up around 28,000 km^2). Here we investigate the location and density of SAR cases relative to available oceanographic datasets in the Central Pacific and run three drift simulations using SAROPS. These case studies allow us to look at SAR statistics relative to available oceanographic resources and identify areas for improvement.

4.1. Remote SAR Case Study: The Hawaiian Islands

There are very few observational data sets available in the Central Pacific that can be pulled into the EDS for use in SAROPS. One observational data set that has recently been tested for use is the

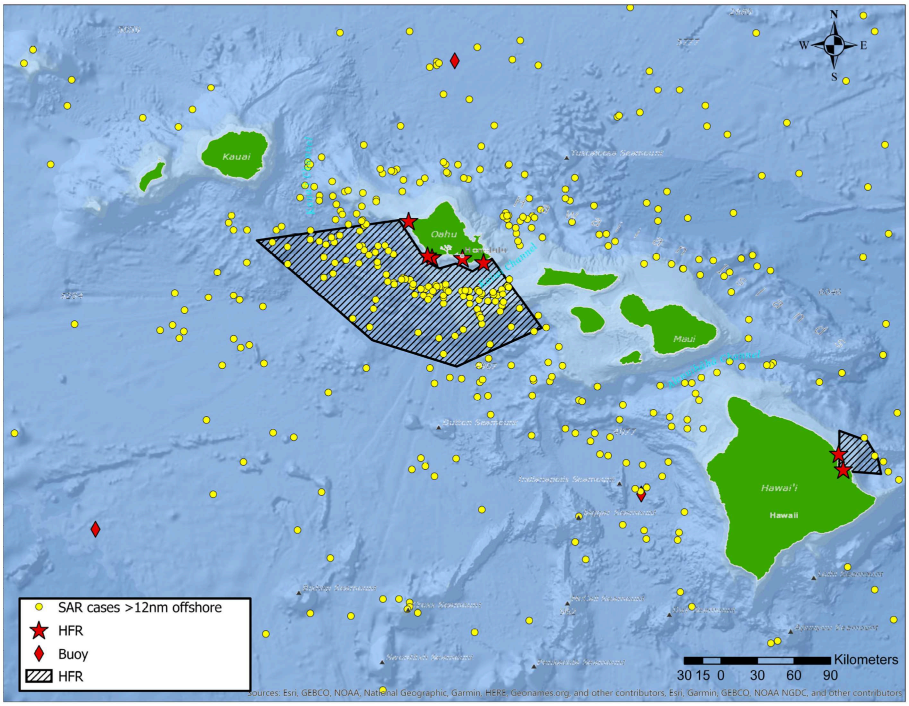

FIGURE 1 | Search and Rescue cases (yellow dots) in the Hawaiian Island region from 2002 through 2018. Only offshore cases (>12 nm from land) are shown. Red stars indicate the locations of High Frequency Radars, red diamonds are the locations of moored surface buoys. The black hatched boxes represents the spatial coverage of the HF Radars.

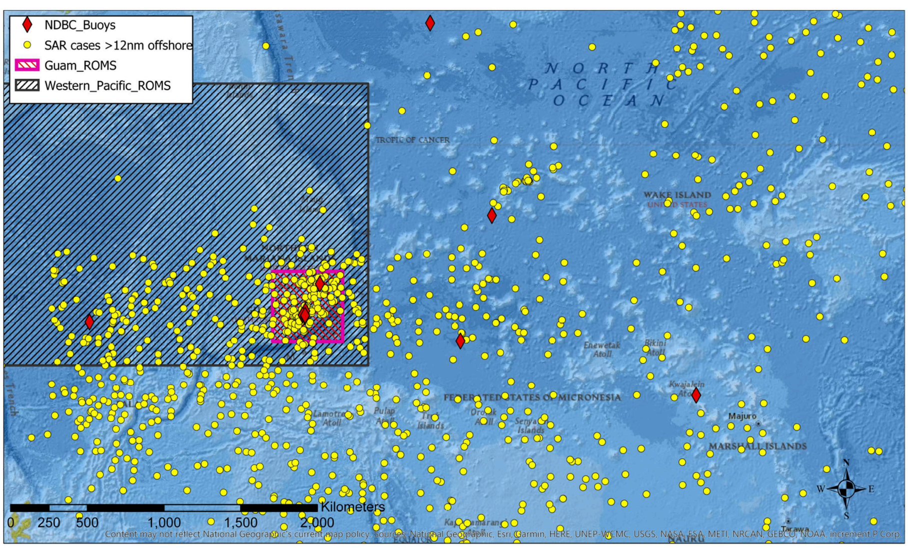

FIGURE 2 | Search and Rescue cases (yellow dots) in the Western Pacific region from 2002 through 2018. Only offshore cases (>12 nm from land) are shown. Red diamonds are the locations of moored surface buoys. The hatched areas represent coverage of ROMS models.

surface portion of the 10-day ARGOS float cycle. While there are close to 4,000 ARGO floats globally in the deep waters, only a few of the open ocean SAR cases can directly benefit from this data set. Most of the observations in the region are located near the main Hawaiian Islands due to the large population center located there. The only HF radar surface current data in the entire Central Pacific is found on the Hawaiian Islands (**Figure 1**). However, coverage is small. Only the southern and western shores of Oahu, and Hilo Bay on the island of Hawaii, are covered by real-time surface current data (red stars shown in **Figure 1**). By comparison, near continuous HF radar surface currents are available from Portland, Oregon to the California-Mexico border. Also, in contrast from the continental United States, there is a lack of STPS for surface currents based on the HF Radar data. The Hawaiian Islands do have a local ROMS model available. The Hawaii Regional Ocean Modeling System (HROMS) is a 4-km resolution ocean model that covers the main Hawaiian Islands. Nested inside are localized, higher resolution models in frequently trafficked areas such as the south shore of Oahu. Further information on HROMS is provided on the Pacific IOOS (PacIOOS) website. Available from PacIOOS is a regional Guam ROMS model with 2km resolution, as well as a Western North Pacific ROMS model with 4 km resolution (**Figure 2**). Outside of those resources, the rest of the Central Pacific is left with only global scale ocean circulation models to conduct drift predictions.

SAR case data in the Pacific were examined using geographical position and case length, in hours (**Figure 1**). Most (66%) search and rescue cases in the Central and Western Pacific occur within 12 nautical miles of land and were excluded from this analysis in order to focus on offshore search and rescue. For these offshore cases only a small percentage fall within the range of the HF radar real-time surface currents (4.5%) while one fifth fall within the Hawaii ROMS model currents (20%). If the Western Pacific and Guam ROMS model currents are added, the total number of offshore cases that are covered by ROMS increases to 40%. A detailed breakdown of SAR cases covered by each data source is provided in **Table 1**. The highest case density occurs near the two main population centers, the Hawaiian Islands (**Figure 1**) and Guam (**Figure 2**). However, once the cases are weighted by the time response assets spent on scene, other areas grow in importance. Since 2002, there have been 146 cases in offshore waters (> 12*nm* from land) that exceeded 36 h with response assets on scene. The majority of these cases occurred in the Western Pacific near Guam, Palau, and the Federated States of Micronesia. Although this represents only 2% of SAR cases, due to the high hourly cost of response assets, these represent long search time and high cost cases with a low probability of success. In these locations, direct observations of ocean currents are sparse, STPS from HF radars is unavailable, and coverage of the data assimilating regional ocean models is unavailable for the Federated States of Micronesia.

TABLE 1 | Percentage of SAR cases covered by available ocean current data sources.

Ocean current source	% of cases covered
HF Radar	4.5
HI ROMS	20
Guam ROMS	6
Western Pacific ROMS	14
Combined ROMS total	40

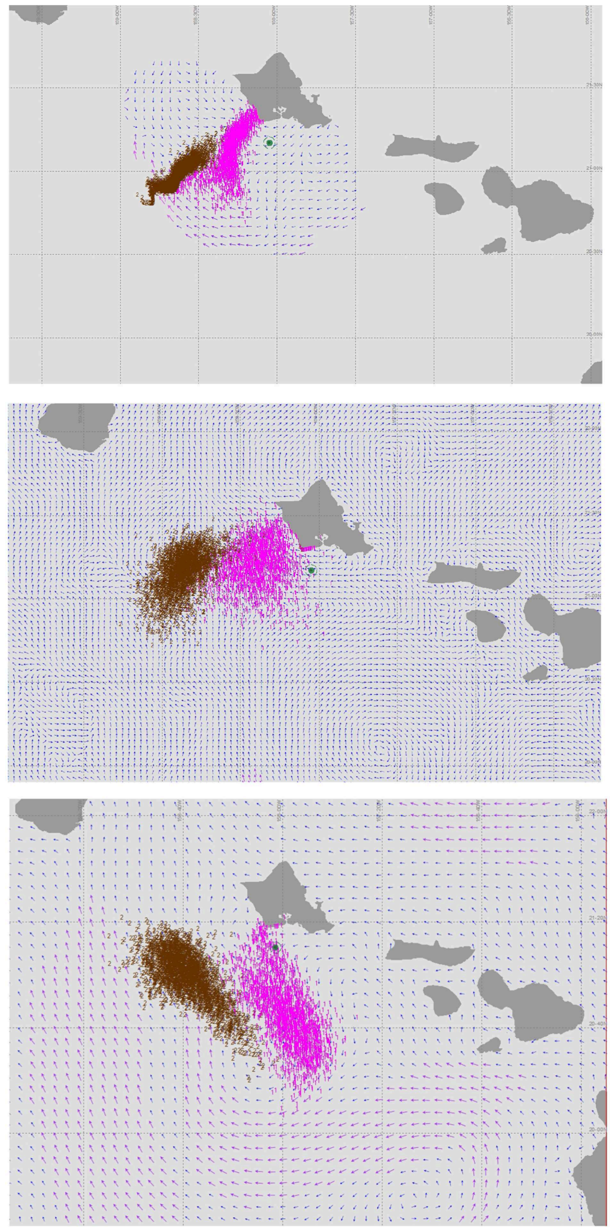

FIGURE 3 | SAROPS output from a simulated SAR case off Oahu. **top**: Particle density map for a 14 foot sit on top kayak (brown) and person in the water (pink) using ocean current data from available HF Radars. **middle**: Particle density map for a 14-foot sit on top kayak (brown) and person in the water (pink) using ocean current data from available HROM. **bottom**: Particle density map for a 14-foot sit on top kayak (brown) and person in the water (pink) using ocean current data from available global HYCOM.

In order to investigate the impact of various observational data on SAR predictions, a drift simulation was conducted near the island of Oahu. The goal of the SAR simulation was to compare drift results from three different surface current data sources: direct observations via HF radar with 2-km horizontal resolution, modeled surface currents from HROMS with 4-km horizontal resolution, and modeled surface currents from Global HYCOM at 1/12° horizontal resolution. Two SAR cases were run simultaneously: a person in the water (PIW) without a lifejacket and a 14′ sit-on-top kayak, both using the most current leeway coefficients available in SAROPS. The case was initiated with a last known position (LKP) for both objects of $21°10.302'N, 158°02.948'W$. The objects were drifted for 48 h. This time frame was chosen because it kept the objects within the coverage of all three respective surface current sources during the whole drift. Additional time allowed both the objects to drift outside the coverage of the HF radar, invalidating the comparison. For all three simulations, the same wind source was used, the Hawaii-based Weather Research and Forecasting (WRF) model at 3-km resolution. Particles were allowed to both run ashore (sticky shoreline) or "bounce" off the shoreline (slippery shoreline). The results of the three drift scenarios are shown in **Figure 3**. Pink particles represent the PIW and brown particles represent the kayak. The drift run using the HF radar (**Figure 3**, top) resulted in the smallest area, with the particles (both PIW and kayak) covering a 2,879 km^2 area, compared to the HROMS run (**Figure 3**, middle) coming in at 7,863 km^2 and HYCOM (**Figure 3**, bottom) with the largest area of 12,196 km^2. These results match previous studies that found that the use of observational data including HF radar reduces search areas by up to a factor of 3 (O'Donnell et al., 2005; Roarty et al., 2010; Kohut et al., 2012).

5. RECOMMENDATIONS

One region in the Central Pacific that is not covered by ROMS is the area to the south of Guam, extending from Palau to the Federated States of Micronesia. This area contains 14.8% of offshore SAR cases, including the majority of the cases lasting longer than 36 h. Increasing available observations in this region could benefit a large percentage of SAR cases. On a smaller scale, near the population hubs of Guam and Hawaii, case dense regions are the southern coast of Guam and the western shores of Hawaii and Maui. Additional coverage here could increase offshore SAR case coverage from 4.5 to 10%.

Another more cost effective alternative to installing additional equipment is to maximize the use of what is already available. Brushett et al. (2017) used consensus modeling to evaluate search prediction effectiveness in the tropical Pacific. Using four different global ocean models, they found that a three or four model consensus search area was greatly reduced from a single model search area with a four model consensus being approximately one third the size of a search area produced by a single model. In addition to the large reduction in search area, they found that for their experiments, the consensus search area always contained the actual found position of the drift object. This is a promising result that suggests in areas with few options, consensus forecasts for SAR objects could reduce search area and decrease individual model error.

6. CONCLUSIONS

Even as sensors and search platforms continue to improve, mariners lost at sea aboard small craft which are difficult to detect, remain a problem for the world's coast guards. Narrowing search areas by accessing accurate, verified surface current fields will go a long way toward successfully locating survivors and survivor craft, both saving lives and saving limited and expensive resource hours. Accessing and fully using all the available oceanographic data sets and numerical models is key to providing accurate predictions for the SAR trajectory models.

AUTHOR CONTRIBUTIONS

VF conceived of the presented idea and performed the case study analysis. VF and AA contributed to the final manuscript.

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REFERENCES

Allen, A. (2005). *Leeway Divergence*. Report No. CG-D-05-05.

Allen, A., and Plourde, J. (1999). *Review of Leeway: Field Experiments and Implementation*. Report No. CG-D-08-99.

Barrick, D., Fernandez, V., and Ferrer, M. (2012). A short-term predictive system for surface currents from a rapidly deployed coastal hf radar network. *Ocean Dynam.* 62, 725–740. doi: 10.1007/s10236-012-0521-0

Bellomo, L., Griffa, A., Cosoli, S., Falco, P., Gerin, R., Iermano, I., et al. (2015). Toward an integrated hf radar network in the mediterranean sea to improve search and rescue and oil spill response: the tosca project experience. *J. Oper. Oceanogr.* 8, 95–107. doi: 10.1080/1755876X.2015.1087184

Berkson, J., Woityra, W., Boda, K., Allen, A., Hicks, M., and Futch, V. (2019). The role of marine science and oceanography in the united states coast guard. *Proc. Coast Guard J. Saf. Secur. Sea* 76, 21–29. Available online at: https://www.dco.uscg.mil/Featured-Content/Proceedings-Magazine/

Breivik, O., and Allen, A. (2008). An operational search and rescue model for the norwegian sea and the north sea. *J. Marine Syst.* 69, 99–113. doi: 10.1016/j.jmarsys.2007.02.010

Breivik, O., Allen, A., Maisondieu, C., and Olagnon, M. (2013). Advances in search and rescue at sea. *Ocean Dyn.* 63, 83–88. doi: 10.1007/s10236-012-0581-1

Brushett, B., Allen, A., Futch, V., King, B., and Lemckert, C. (2014). Determining the leeway drift characteristics of tropical pacific island craft. *Appl. Ocean Res.* 44, 92–101. doi: 10.1016/j.apor.2013.11.004

Brushett, B., Allen, A., King, B., and Lemckert, C. (2017). Application of leeway drift data to predict the drift of panga skiffs: Case study of martime search and rescue in the tropical pacific. *Appl. Ocean Res.* 67, 109–124. doi: 10.1016/j.apor.2017.07.004

Cho, K.-H., Li, Y., Wang, H., Park, K.-S., Choi, J.-Y., Shin, K.-I., et al. (2014). Development and validation of an operational search and rescue modeling system for the yellow sea and the east and south china seas. *J. Atmom. Ocean. Tech.* 31, 197–215. doi: 10.1175/JTECH-D-13-00097.1

Cummings, J., Bertino, L., Brasseur, P., Fukumori, I., Kamachi, M., Martin, M., et al. (2009). Ocean data assimilation systems for godae. *Oceanography.* 22, 96–109. doi: 10.5670/oceanog.2009.69

Di Maio, A., Martin, M., and Sorgente, R. (2016). Evaluation of the search and rescue leeway model in the tyrrhenian sea: a new point of view. *Nat. Hazards Earth Syst. Sci.* 16, 1979–1997. doi: 10.5194/nhess-16-1979-2016

Frolov, S., Paduan, J., and Cook, M. (2012). Improved statistical prediction of surface currents based on historic hf-radar observations. *Ocean Dynam.* 62, 1111–1122. doi: 10.1007/s10236-012-0553-5

Frost, J., and Stone, L. (2001). *Review of Search Theory: Advances and Applications to Search and Rescue Decision Support*. USCG Research and Development Center. Report No. CG-D-15-01.

Hackett, B., Breivik, O., and Wettre, C. (2006). "Forecasting the drift of objects and substances in the oceans," in *Oceans Weather Forecasting: An Integrated View of Oceanography*, eds E. P. Chassignet and J. Verron (Dordrecht: Springer), 507–524.

Harlan, J., Allen, A., Howlett, E., Terrill, E., Kim, S., Otero, M., et al. (2011). "National ioos high frequency radar search and rescue project," in *OCEANS'11 MTS/IEEE KONA* (Waikoloa, HI).

Hodgins, D., and Hodgins, S. (1998). *Phase II Leeway Dynamics Study Program Development and Verification of a Mathematical Drift Model for Liferafts and Small Boats*. Prepared for Canadian Coast Guard College, Dept. Fisheries and Oceans.

Kohut, J., Roarty, H., and Randall-Goodwin, E. (2012). Evaluation of two algorithms for a network of coastal hf radars in the mid-atlantic bight. *Ocean Dynam.* 62, 953–968. doi: 10.1007/s10236-012-0533-9

Le Traon, P. (2013). Efrom satellite altimetry to argo and operational oceanography: three revolutions in oceanography. *Ocean Sci.* 9, 901–915. doi: 10.5194/os-9-901-2013

Martin, M., Balmaseda, M., Bertino, L., Brasseur, P., Brassington, G., Cummings, J., et al. (2015). Status and future of data assimilation in operational oceanography. *J. Oper. Oceanogr.* 8, s28–s48. doi: 10.1080/1755876X.2015.1022055

O'Donnell, J., Ullman, D., Spaulding, M., Howlett, E., Fake, T., Hall, P., et al. (2005). *Integration of Coastal Ocean Dynamics Application Radar (codar) and Short-Term Predictive System (stps) Surface Current Estimates Into the Search and Rescue Optimal Planning System (sarops)*. Report No. CG-D-01-2006.

Oke, P., and Schiller, A. (2007). Impact of argo, sst, and altimeter data on eddy-resolving ocean reanalysis. *Geophys. Res. Lett.* 34:L19601. doi: 10.1029/2007GL031549

Roarty, H., Allen, A., Glenn, S., Kohut, J., Nazzaro, L., and Fredj, E. (2018). *Evaluation of Environmental Data for Search and Rescue II*. Kobe: OCEANS 2018.

Roarty, H., Glenn, S., and Allen, A. (2016). *Evaluation of Environmental Data for Search and Rescue*. Shanghai: OCEANS 2016.

Roarty, H., Glenn, S., Kohut, J., Gong, D., Handel, E., Rivera Lemus, E., et al. (2010). Operation and application of a regional high frequency radar network in the mid atlantic bight. *Mar. Technol. Soc. J.* 44, 133–145. doi: 10.4031/MTSJ.44.6.5

Ullman, D., O'Donnell, J., Edwards, C., Fake, T., Morschauser, D., Sprague, M., et al. (2003). *Use of Coastal Ocean Dynamics Application Radar (Codar) Technology in U.S. Coast Guard Search and Rescue Planning*. Report No. CG-D-09-03.

Wilkin, J., Rosenfeld, L., Allen, A., Baltes, R., Baptista, A., He, R., et al. (2017). Advancing coastal ocean modelling, analysis, and prediction for the u.s. integrated ocean observing system. *J. Oper. Oceanogr.* 10, 115–126. doi: 10.1080/1755876X.2017.1322026

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Seafloor Mapping – The Challenge of a Truly Global Ocean Bathymetry

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Detailed knowledge of the shape of the seafloor is crucial to humankind. Bathymetry data is critical for safety of navigation and is used for many other applications. In an era of ongoing environmental degradation worldwide, bathymetry data (and the knowledge derived from it) play a pivotal role in using and managing the world's oceans in a way that is in accordance with the United Nations Sustainable Development Goal 14 – conserve and sustainably use the oceans, seas and marine resources for sustainable development. However, the vast majority of our oceans is still virtually unmapped, unobserved, and unexplored. Only a small fraction of the seafloor has been systematically mapped by direct measurement. The remaining bathymetry is predicted from satellite altimeter data, providing only an approximate estimation of the shape of the seafloor. Several global and regional initiatives are underway to change this situation. This paper presents a selection of these initiatives as best practice examples for bathymetry data collection, compilation and open data sharing as well as the Nippon Foundation-GEBCO (The General Bathymetric Chart of the Oceans) Seabed 2030 Project that complements and leverages these initiatives and promotes international collaboration and partnership. Several non-traditional data collection opportunities are looked at that are currently gaining momentum as well as new and innovative technologies that can increase the efficiency of collecting bathymetric data. Finally, recommendations are given toward a possible way forward into the future of seafloor mapping and toward achieving the goal of a truly global ocean bathymetry.

Keywords: bathymetry, seafloor, mapping, GEBCO, seabed 2030, SDG14

INTRODUCTION

The world's oceans cover 71% of the Earth. This is about 362 million square kilometers of the total surface area (Eakins and Sharman, 2010), but only a small fraction has been mapped by direct observation. The last few years have seen a resurgence in the recognition of the importance of seafloor mapping and many national and international initiatives are currently underway. Recent tragedies such as the disappearance of Malaysia Airlines flight MH370 as well as natural disasters, habitat loss and the increasing demand for offshore energy and marine resources have highlighted the need for better knowledge of the seafloor (e.g., Smith et al., 2017). In 2015, the sustainable development of our oceans was targeted in the sustainable development goals (SDG) of the United Nations (UN) that aim to achieve a better and more sustainable future for all by 2030. Goal 14 – Life below water – aims to conserve and sustainably use the oceans, seas and marine resources through enhanced scientific knowledge and research capacity amongst other things (United Nations, 2015). In 2017, the UN proclaimed the Decade of Ocean Science for Sustainable Development (2021–2030) to promote sustainable ocean management highlighting the need for ocean observation and ocean research. At the same time, the Nippon Foundation-GEBCO Seabed 2030 Project issued the challenge to survey the ocean floor across the globe by 2030. In addition, inter-governmental agreements, including the Galway Statement (2013) for the North Atlantic and the Belém Statement (2017) for the whole Atlantic, seek to encourage collaborative ocean research with bathymetric mapping at their core. All of these initiatives have provided a strong push to better understand our oceans and have also increased awareness of the advantages of data sharing, by both research and commercial sectors, to reduce duplication of effort and mitigate environmental impacts.

Despite collecting data for centuries and, in recent decades, the introduction of new and improved sounding techniques, the depth of the ocean has been determined over less than 18% of the seafloor using echo-sounders at a resolution of about 1 km (Mayer et al., 2018). The current rate of progress is not sufficient to complete the task of mapping the world's oceans in the near future without international collaboration, appropriate strategies and significant technological developments. Large parts of the area beyond the limits of national jurisdiction, where the international seabed authority (ISA) organizes and controls resource-related activities on the seabed and subsoil (United Nations, 1982), are still unmapped. Exceptions are areas of interest for the marine industry and exploration areas that are allocated to contractors by the ISA for exploring deep-sea mineral resources. Seafloor exploration is also well-advanced in exclusive economic zones (EEZs) of coastal states that have the capabilities and facilities to conduct mapping surveys. For a better understanding of the marine environment and the development of sustainable ocean management regimes, a comprehensive and systematic survey of the world's ocean floor is essential.

This paper reviews the efforts made so far to produce a truly global ocean bathymetry map derived from direct observation. An overview of the current state of seafloor mapping is presented with a main focus on large-scale ocean mapping solutions. Starting with an outline of the history of seafloor mapping leading up to recent developments including data compilation efforts, it highlights the importance of bathymetric data and gives examples of their use for societal and environmental benefits. Then a selection of repositories and syntheses is presented as best practice examples for bathymetry data compilation, archiving of source data, data discoverability and availability. All these initiatives require a strategy that can combine the efforts to accomplish the task of mapping the world's oceans. The Nippon Foundation-GEBCO Seabed 2030 Project aspires to facilitate this through global coordination and capacity building, and is briefly introduced in this context. The challenge of mapping the gaps will be discussed and the seafloor community network with its main linkages illustrated. Finally, an outlook is given toward the future of seafloor mapping, including key recommendations.

THE HISTORY OF SEAFLOOR MAPPING

How Do We Map?

Bathymetry deals with the topography of the seafloor. The history of this branch of hydrography goes back more than 3,000 years, with the first evidence of water depth measurements in historical records from ancient Egypt (Theberge, 1989). The first measuring devices were sounding poles and lines with weights attached to them. The first large-scale scientific application using lead weights occurred during the HMS *Challenger* oceanographic expedition around the globe in the 1870s. Such "plumb-line" measurements were the standard practice until the beginning of the 20th century.

The foundation for replacing plumb-lines with acoustic techniques was laid at the end of the 15th century, when Leonardo da Vinci discovered that ship noise could be heard under water from afar, thereby discovering that sound travels under water (Urick, 1983). Nowadays, a large proportion of the information we receive from ocean environments is brought to us by sound waves, similar to the information carried by electromagnetic waves above water. The trigger for further development of underwater acoustic techniques in the beginning of the 20th century was the need to detect underwater objects, exemplified by the search for the Titanic that sank in 1912, as well as submarine warfare during World War I (Lurton, 2002). This time marks the start of the echo sounding era.

Single Beam Echo-Sounders (SBES)

The development of SBESs constituted a significant improvement in terms of accuracy and efficiency over earlier equipment. SBESs are configured with piezoelectric crystal- or ceramic-based transducers that can generate and receive acoustic signals. The depth of the seafloor is determined by measuring the two-way travel time of a sound wave that is sent toward the seafloor and back. This technique combined with accurate measurements of acoustic wave travel time laid the foundation for this success story (Mayer, 2006).

Multibeam Echo-Sounders (MBES)

Multibeam echo-sounder systems became publically available in the 1970s (e.g., Glenn, 1970; Renard and Allenou, 1979), coincident with the development of the satellite-based navigation system global positioning system (GPS), enabling high spatial accuracy for environmental measurements globally. Multibeam systems radiate a fan of sound and listen to the returning echoes of the emitted signals in narrow sectors perpendicular to that fan, resulting in the mapping of a swath of seafloor instead of just a line. They have the advantage of collecting higher-resolution bathymetric data and of making mapping efforts much more efficient, by mapping an area in a much shorter time compared to SBESs. Modern systems can have many hundreds of beams and can achieve swath angles between 120 and 150 degrees.

The area on the seafloor that an acoustic beam ensonifies is mainly dependent on beam widths of the transmit and receive beams, the opening angle chosen by the surveyor and the water depth. Small angles and shallow water depths generally result in smaller "acoustic footprints" and therefore higher-resolution data than large angles and deeper water depths, due to the expansion of the beam as it travels through the water column (Lurton, 2002). This means that very high-resolution data can be obtained using ships in shallow water, but that the resolution decreases with increasing water depth. In deep water, vehicles operated near the seafloor can address this challenge.

Satellite-Derived Bathymetry (SDB)

Two other seafloor mapping techniques are used in coastal environments. Collecting bathymetric data with ship-based systems in shallow water is substantially more time-consuming and hazardous than collecting deep-water data. SDB from multispectral satellite imagery, developed in the 1970s, can be used to map shallow areas where water clarity permits. Satellite platforms collect data in multiple spectral bands, spanning the visible through infrared portions of the electromagnetic spectrum. Water depth estimations are based on the attenuation of radiance as a function of depth and wavelength in the water column (Pe'eri et al., 2014; IHO and IOC, 2018).

Light Detection and Ranging (LIDAR)

Another option to map shallow areas is the use of bathymetric LIDAR, a technique that transmits laser pulses from an airborne platform and measures their return. The water depth is calculated from the time difference between the reflection from the water surface and the reflection from the seafloor (Irish and White, 1998). However, the use of such optical solutions is limited to shallow areas with optimal water clarity.

Satellite Altimetry

The first altimetric satellites were launched in the 1970s. Altimeters do not directly measure ocean depth, but the height of the ocean's surface, which is affected, among other things, by the gravitational effects of topographic features on the seafloor. When the first satellite-altimetry derived digital terrain model (DTM) was first released it revolutionized the study of plate tectonics. Altimetry data have far lower horizontal resolution than ship's bathymetry and provide depth estimates which are inherently under-determined. They can, however, reveal large geomorphological features of the ocean floor. Resolution of features with horizontal scales as small as 6–9 km can be achieved under ideal conditions in the deep ocean (Sandwell et al., 2006). Smith and Sandwell (1997) published a topographic map of the world's oceans with a resolution between 1 and 12 km, by combining depth soundings from ships and marine gravity data from satellite altimetry. The gravity models on which the topographic maps are based have been updated several times since (Sandwell et al., 2014).

Current Developments and Future Plans

In order to convert depth soundings into a bathymetric surface, several steps need to be taken. There is a trend toward the development of effective automation routines that include data acquisition, vessel-to-shore data transmission and data processing. The Shell Ocean Discovery XPRIZE challenge (2015–2019) – Discovering the Mysteries of the Deep Sea – designed to accelerate innovation for the rapid and unmanned exploration of the seafloor, is one example that addresses a need for new technologies in order to meet the goals of various ocean initiatives.

Autonomous Systems

Modern multibeam echo-sounders have a size and power consumption that makes them suitable for autonomous operations. The use of autonomous surface vehicles (ASV) and autonomous underwater vehicles (AUV) equipped with such echosounders can release ships from dedicated mapping activities (**Figure 1**). The time and human resources (and therefore costs) associated with the ship-based acquisition of bathymetric data can be considerable. Industry-leading companies are developing vessel-to-shore communication systems to reduce the number of people needed on board and at the same time enable full survey operability (e.g., Haugen, 2018). Improved vessel-to-shore communication not only provide means to remotely control survey operations, but can also ensure rapid and autonomous delivery of newly acquired multibeam data to research institutes,

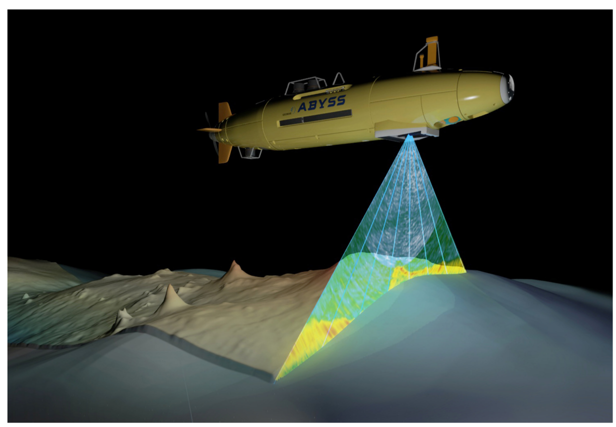

FIGURE 1 | Artistic impression of an AUV performing a deep-sea multibeam survey (courtesy of Tom Kwasnitschka/Nico Augustin, GEOMAR).

survey companies and ideally data repositories. Communication may still be limited by bandwidth and high costs restricting the transfer of the large volumes of data. An alternative strategy is to process data automatically on the vessel and create products that are small enough to be easily transferred over the available connection (e.g., Hamilton, 2018).

Making data acquisition autonomous can also reduce safety risks by allowing operators to stay away from hazardous situations and still access traditionally inaccessible regions, e.g., under ice or navigationally complex areas, such as shallow waters, steep slopes or volcanic areas (e.g., Lucieer et al., 2016; Carlon, 2018). Furthermore, in deep water AUVs and remotely operated vehicles (ROV) can obtain multibeam data with a much higher resolution than ship-based systems, since they are not limited to the sea surface (Wynn et al., 2014; Kelley et al., 2016; Lucieer and Forrest, 2016) with the most advanced vehicles reaching water depths of almost 11,000 m (e.g., Bowen et al., 2007). While ROVs are remotely piloted and powered from a ship, AUVs operate independently, with their range only limited by their onboard power supply (Huvenne et al., 2018). The deployment of these near-bottom mapping systems is currently still inefficient for the mapping of large areas, partly because of their slow speeds compared to ships. However, in the case of AUVs this can be compensated for by multiple vehicles working in tandem. Furthermore, the positioning accuracy for AUVs is still limited, and at present, they are not able to make ship-based surveys obsolete, since it is still essential to roughly understand the bathymetry of an area before a submersible can be sent down toward the seafloor.

Automated Data Processing and Quality Assurance

The processing of raw multibeam data into a high-quality data product, often a gridded DTM at the best possible resolution, can take a considerable amount of time and resources for data cleaning, integration of auxiliary data and gridding (Lamarche et al., 2016). Multiple efforts are underway to accelerate this process, especially with regard to ever-increasing data volumes. With adequate data density achieved by overlapping survey lines, statistical filters can be used for automated data cleaning to identify and exclude spikes or outliers, but with marginal time benefit. Modern bathymetry processing software all offer some level of filters and automation, but careful human review of the product is still needed. In an effort to further improve efficiency of data cleaning and processing, the CUBE (Combined Uncertainty Bathymetry Estimate) model was developed (Calder and Mayer, 2003). As part of this procedure, the TPU (Total Propagated Uncertainty) is calculated for each sounding, which combines information about positional accuracy, environmental conditions and system performance into one value. The TPU is used to weight the contributions of each sounding to the estimate of depth at a defined position (grid node). Apart from this, other automatic methods for reliably reducing the volume of the bathymetric data have been proposed (e.g., Rezvani et al., 2015). Generally speaking, the automated processing of multibeam datasets, while potentially offering ways to minimize processing and other resources associated with acquisition, may in some cases result in loss of information and propagation of errors.

Furthermore, in order to ensure fit-for-purpose bathymetric data, a quality assurance (QA) process is needed. It usually encompasses manual effort and working with a number of different tools to verify and validate acquired data against a range of issues like file corruption, accuracy and consistency, coverage holes or artifacts in the data. The IHO has already developed Standards for Hydrographic Surveys (International Hydrographic Bureau, 2008) that provide minimum standards to help improve the safety of navigation. However, in comparison with other technologies, seabed mapping has less standardization across the community. Hence, a QA process can contribute to building best practices of data acquisition and processing and facilitates the compilation of collected data.

WHY DO WE NEED BATHYMETRIC DATA?

Knowledge of bathymetry is important for a wide variety of uses starting with the fundamental understanding of geological and oceanographic processes affecting our planet. Early echo-sounding profiles across the Atlantic Ocean for instance enabled Bruce Heezen and Marie Tharp to understand the relationship between mid-ocean ridges and earthquake seismicity and played an important part in the recognition of one of the most significant paradigm shifts in science – the development of the hypothesis of seafloor spreading and plate tectonics (Hess, 1962).

A seabed mapping user survey conducted in 2018 by Geoscience Australia and FrontierSI captured information from national and international stakeholders across all sectors. It revealed that habitat mapping and hydrographic charting were the most common applications for the use of high-resolution bathymetric data (Amirebrahimi et al., in press).

Seafloor bathymetry is essential for safety of navigation and for establishing the limits of the extended continental shelf (ECS) under the United Nations Convention on Law of the Sea (UNCLOS) (Jakobsson et al., 2003). This exemplifies that a detailed knowledge of a nation's coastal bathymetry is also vital for political and commercial purposes. A few other examples for the use of bathymetric data are looked at in more detail below.

MH370

The recent loss of Malaysia Airlines flight MH370 has highlighted the lack of detailed bathymetry in large areas of the world's oceans. The existing data in the search area were based on a bathymetric model derived from marine gravity information estimated from satellite-altimetry combined with sonar soundings (Smith and Sandwell, 1997). At the time of the search for the fuselage, single and multibeam data coverage in the area was insufficient to deploy deep-water instruments to provide a detailed inspection of the seafloor (Picard et al., 2017) and so ship-based bathymetric data had to be collected. By comparing this newly acquired high-resolution data with the modeled data (**Figure 2**), it was found that 38% of the grid cells differed vertically from the high-resolution data by more than 100 m with maximum differences of 1900 m (Picard et al., 2018).

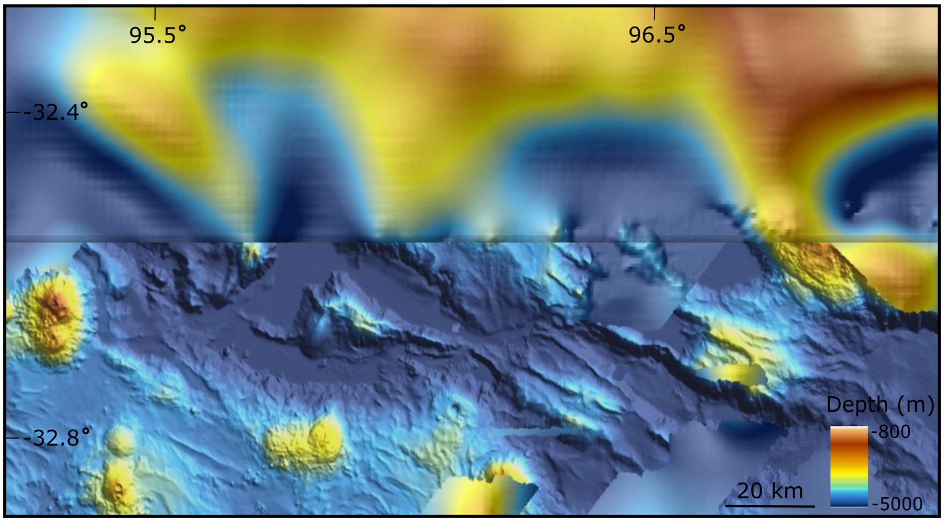

FIGURE 2 | Plan view of the Diamantina trench seafloor area in the Southeast Indian Ocean. The curtain image shows from top to bottom the data resolution increase between altimetry derived bathymetry data, sourced from the SRTM15_PLUS model (Olson et al., 2016), and multibeam bathymetry, gridded at 110 m horizontal resolution, that was acquired to assist the search for Malaysia Airline flight MH370. Image modified from the MH370 storymap (Australian Government, 2017).

Hazard Studies

Marine geohazards are not only of concern to coastal communities, but also to industries dealing with marine infrastructure. Geohazard assessments in the marine realm are mainly based on bathymetric data. Although only a snapshot in time, bathymetric data deepens the understanding of the seafloor fabric and helps to identify potential risks linked to hazardous processes, such as slope failures or turbidity currents, and with repeat surveys, can be used to monitor seafloor changes over time (Chiocci et al., 2011). Clearly, bathymetric resolution appropriate to the target features is required. The morphology of the seafloor is also linked to the formation and propagation of tsunamis and is of vital importance in the context of tsunami forecasting. Generally, bathymetric data represent a fundamental dataset for addressing the growing challenges associated with climate change (Stocker et al., 2013; Fenty et al., 2016).

Ocean Circulation Models

Bathymetric data are also fundamental to our ability to model ocean circulation, with the predicted location of key circulation features, such as the separation point of the Gulf Stream from the United States' coast, being critically dependent on accurate topography representation in the model in question (Thompson and Sallée, 2012; Gula et al., 2015). Similarly, accurate ocean models can have a major impact on the ability of climate models to simulate global phenomena such as El Niño events (e.g., Santoso et al., 2011). The resolution requirements of bathymetry data for the models are limited by the resolution that the ocean models themselves are able to achieve. As this resolution is increasing all the time, there is a growing need for better-resolved seafloor bathymetry.

Seafloor Installations

Marine infrastructure development, such as cable laying, pipeline and platform installation, rig anchoring, or deployment of machines requires high-resolution bathymetric data. Environmental assessments, a requirement prior to any industrial activity affecting the seafloor, starts with a geomorphometric analysis of the region. The need for high-resolution bathymetric data for monitoring of seabed activities will increase in the future (Clark et al., 2017; Ellis et al., 2017). Identification and characterization of areas suitable for seafloor mining also rely on precise bathymetric information (e.g., Hein et al., 2009). For instance, areas of seafloor mineralization from hydrothermal vent systems can be predicted using high-resolution bathymetric data.

Marine Conservation

Precise seafloor information, foremost high-resolution bathymetric data, is required to work toward the goal of protecting at least 10% of the world's oceans by 2020 (UN Convention on Biodiversity Aichi Target 11, Sala et al., 2018) and to support the achievement of SDG 14 – Life below water – of the Agenda 2030 for Sustainable Development. Marine protected areas (MPA) are designated for the protection of the marine environment, but in most cases their initial designation and the development of management plans is hampered by a lack of accurate knowledge about the distribution of marine species and habitats. The direct visual observation of every part of the seafloor for this purpose is an unrealistic expectation, hence environmental parameters are increasingly used for habitat predictions (Howell et al., 2011 Rengstorf et al., 2014). Particularly for benthic species, bathymetry has turned out to be one of the main driving factors behind species distribution. In addition to depth information, associated variables such as slope, aspect, curvature and terrain variability have been demonstrated to act as significant predictors in benthic species distribution models (Wilson et al., 2007). Particularly in areas where biological information is absent, the availability of reliable bathymetric data provides environmental managers with the chance to create a basic habitat map to guide the development of management plans.

BATHYMETRIC DATA SOURCES

One large source, by area, of high-quality bathymetric data is from research cruises, undertaken by a range of research and government institutions across the globe. Data are traditionally held by the host institutions and used for specific research purposes. Exceptions are individual agreements with, for example, funding agencies that oblige institutions to make their data publicly available after a certain amount of time. With more widely accepted data sharing policies, institutions are encouraged to archive their data on central open-access repositories and portals, where data can be easily discovered and freely accessed for wider purposes. This way data are collected once and can be used many times. Sharing these data for re-use ensures that new data acquisition efforts can focus on unmapped regions and maximizes return on public investment.

Within a country's EEZ, national hydrographic offices are usually responsible for the mapping efforts. For many parts of the world, these are closely linked to military organizations, reflecting the key importance of bathymetry for naval and defense operations. Hydrographic offices are legally responsible for the safety of navigation under the International Convention for the safety of life at sea (SOLAS) 1974. Given the physical constraints on gathering large areas of bathymetry in shallow water described above, these data are often expensive to acquire in terms of ship-time. Some national hydrographic offices are joining a growing trend of granting access to their holdings. However, the sensitivity related to national security of some of these data is limiting access to bathymetric information.

Another source of significant amounts of bathymetric data is commercial survey companies. As commercial exploration and exploitation of the marine environment becomes more extensive, commercial survey companies operate to provide high-resolution survey data to their commercial customers. Whilst the extent of these data may be limited to areas with potential for economic development, they are often of very high resolution and high quality. Since the customers are usually the data owners, it has been uncommon on the past for these data to be made available in the public domain. Some survey companies, however, are spearheading an effort to communicate the wider significance and societal benefit of these data to their customers, opening up the possibility of significantly increased public access to these data in the future.

Transit Data – Making the Most of Every Nautical Mile

Research vessels that operate internationally usually have long transit routes, whether transiting from port to study area or between different study areas. Often these routes lead them through international waters, where data recording is unrestricted. Several nations have procedures in place to collect such data and make them publicly available.

In the United States, the Rolling Deck to Repository (R2R) Program was initiated in 2009 to ensure that all underway data acquired aboard the United States Academic Research Fleet is documented and archived in public repositories. Data from each cruise are routinely submitted by the vessel operator to R2R which ensures delivery to the appropriate national repository. This project has resulted in a significant increase of multibeam data made available at the International Hydrographic Organization Data Centre for Digital Bathymetry (IHO DCDB). In 2011, the Multibeam Advisory Committee, was formed to help coordinate fleet-wide multibeam calibrations and system monitoring for the United States Academic Research Fleet and to develop and make publicly available tools and best practices for operational procedures that promote the acquisition of high-quality multibeam data. These projects share the common goal of promoting high-quality publicly available data and encourage the acquisition of transit data.

In 2015, three German research vessels (RV *Maria S. Merian*, RV *Meteor*, and RV *Sonne*) started to collect multibeam data on their transit routes, mapping approximately 200,000 km^2 every year. Recently, RV *Polarstern*, a fourth German research vessel and the Dutch RV *Pelagia* have announced an intention to join this approach. The transit data are sent to GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany, where the data are processed and several data products created. The data are integrated into the international Pangaea Data Publisher for Earth and Environmental Science as well as into the IHO DCDB. Data collection is actively supported by the ship's crew and usually by the chief scientists. Of key importance for getting this support has been the commitment to make the data freely available for all.

Another supporting example that transit matters is the search for flight MH370. Seabed mapping contractors were asked and agreed very early on to acquire data (at no cost) during transit between the search area and the port-of-call, and where possible, to build on the coverage. After over 3 years of operation, transit data accounted for $\sim$432,000 km^2, the equivalent of 1.5 time the search area (238,000 km^2). This data was of similar resolution to the search area, however, it is of lesser quality and density due to the nature of transit acquisition. Overall, the data collected for the search of the flight MH370 was made freely available, but still only accounts for 1% of the Indian Ocean seafloor (Picard et al., 2017).

Crowdsourced Bathymetry

The IHO has a history of encouraging both innovative ways to gather data and data maximizing initiatives to gain a better understanding of the bathymetry of the seas, oceans and coastal waters. In 2014, the IHO, at its Fifth Extraordinary International Hydrographic Conference, recognized that traditional survey vessels alone could not be relied upon to solve our data deficiency issues and agreed there was a need to encourage and support all mariners in an effort to "map the gaps." One outcome of the conference was an initiative to support and enable mariners and professionally manned vessels to collect crowdsourced bathymetry (CSB) to be used as a powerful source of information to supplement the more rigorous and scientific bathymetric coverage generated by hydrographic offices, industry, and researchers around the world.

An IHO CSB Working Group, comprising international scientific, governmental and commercial hydrographic experts, was tasked by the IHO to draft a guidance document meant to empower as many mariners as possible to map the gaps in the bathymetric coverage of the world's ocean. The document, which will become an adopted IHO publication in 2019, describes what constitutes CSB, the installation and use of data loggers, preferred data formats, and instructions for submitting data to the IHO DCDB. The document also provides information about data uncertainty to help data collectors and data users better understand quality and accuracy issues with CSB. The working group is now focusing on developing an outreach plan covering the "why, what, where, and how" to encourage all vessels at sea to collect bathymetric data as part of a mariner's routine operations.

Under the guidance of the working group, NOAA's national centers for environmental information (NCEI) has implemented the ability to archive, discover, display and retrieve global crowdsourced bathymetric data contributed from mariners around the world. These data reside in the IHO DCDB which offers access to archives of oceanic, atmospheric, geophysical, and coastal data (Jencks et al. "Citizen-Science for the Future: Advisory Case Studies from Around the Globe," this issue).

Release of Data From National Archives

Many countries hold large amounts of bathymetric data, but it is often difficult to get access to this data. Countries providing unrestricted access to their data holdings are still an exception. A country's bathymetric data might ideally be archived in a national data repository, but in reality is often distributed over several data archives and institutional repositories throughout the country. Few of these archives have open access policies, accordingly, the data are not freely available for others. Data that are freely available are often not directly downloadable, they are only available upon request. Another challenge is that national data archives are often only known in the respective country but not abroad, which makes it difficult to find data.

The availability of bathymetric data is regulated by each country's national legislation. If a country decides to make its data available, the question remains of how to make the data discoverable and accessible to the interested user. Several bathymetric syntheses, some of which are described below, are addressing this question. Another collaborative approach has been started by the EU Horizon 2020 research and innovation project AtlantOS *Optimizing and Enhancing the Integrated Atlantic Ocean Observing System*. The project covers various disciplines, including seafloor mapping, with the objective of enhancing ship-based observing networks. Within this approach, several European data centers are working together to trace deep-sea bathymetric data and integrate them to the IHO DCDB in order to make them accessible and usable for the specialist and non-specialist user. A standard workflow regarding data integration into the IHO DCDB, including metadata provision and data transfer, has been successfully established for future data transfer.

Release of Private and Commercial Data

A source of bathymetric data that has, until recently, been poorly exploited, is the wealth of data being collected by commercial surveying companies. For the most part, these data are owned by the customers of the survey companies that collect them. As a result, the primary survey data cannot be placed in the public domain or contributed to mapping projects without the express permission of those customers.

Based on their user survey, Amirebrahimi et al. (in press) highlighted that most participating organizations are willing to contribute to national or international mapping initiatives. However, this is usually done on a case-by-case basis. The unwillingness of private companies or their clients to have their data contributed to public domain was directly linked to the financial side of data capture and establishing appropriate license for use of the data. By covering the cost of data acquisition, organizations often consider the data their intellectual property and accordingly, are not willing to easily share them with others. Additional barriers for releasing data may include but are not limited to security considerations and confidentiality of data. The perceived sensitivity of the data is sometimes so high that organizations are not even willing to publish the coverage or the metadata of the survey data.

GEBCO is working to build relationships with survey companies and their customers to release the data they hold or own. The first agreement was made in early 2018 with Fugro, a large offshore company providing geotechnical and survey services, who acquire vast quantities of bathymetric data with a global fleet of ocean-going survey vessels. As they move vessels from project to project, they also have the opportunity to collect data during transits as a form of CSB contribution. Since commencing the program, over 167,000 km^2 of multibeam bathymetric data have been contributed to the IHO DCDB.

In addition, Fugro has begun to make their customers aware of this approach and has begun to explore if there are any terms under which they might consider donations of data. In many cases, as mentioned above, these datasets may contain market-sensitive information and when this is the case, it is determined if a reduction in resolution and/or a delay in release may mitigate any data sensitivity concerns. In the first instance, provision of simple metadata to allow identification of the area of data coverage and data characteristics is a step forward in identifying the areas of seafloor that have already been surveyed, even if the data cannot yet be released.

Following the success of the Fugro initiative, further collaborations are now being developed with other commercial partners. The best-practice being developed, promoting public access to the transit data through IHO DCDB combined with potentially limited release of commercially sensitive data, is now being encouraged across the marine survey industry. It is expected that this approach will not eliminate the need for marine site characterization services, but rather increase its demand. Only through a comprehensive mapping of the ocean will areas of interest become known. The expectation is that within those areas of interest, high-resolution mapping services will still be required to support marine projects and activities.

BATHYMETRIC DATA REPOSITORIES AND SYNTHESES

Data centers act as central repositories for the secure archiving of source data and ideally provide resources for data discoverability and access. There are many international, regional and national repositories, including some national hydrographic offices, that serve this function. While we recognize the efforts of some nations in building and managing national data centers [e.g., Australia with the Geoscience Australia's Marine Data Portal, Japan with DARWIN from the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), or France with data.shom.fr from the French Hydrographic and Oceanographic Service], we have deliberately chosen to focus on one international data repository and several bathymetric syntheses providing bathymetric data products. In this section, we will introduce some examples and examine their wider international linkages regarding data sharing as demonstrations of best practices. The examples presented here are not intended as an exhaustive list.

The IHO DCDB

The International Hydrographic Organization Data Centre for Digital Bathymetry (IHO DCDB) was established in 1990 to steward the worldwide collection of bathymetric data. The intent was for the center to archive and share, freely and without restrictions, raw unedited single- and multibeam bathymetric data acquired by hydrographic, oceanographic and other vessels. In the original proposal, the former NOAA national geophysical data center (NGDC), now the NCEI, agreed to "operate a worldwide digital data bank of oceanic bathymetry on behalf of the Member States of the IHO."

Almost 30 years later, NCEI and the DCDB remain committed to providing easy, open access to the wealth of data from a variety of sectors (e.g., industry, government, academia, crowdsource efforts) for long-term archive, stewardship, and public use. Enabling users to locate and access the data they need is critical in maximizing the re-use of data. NCEI accomplishes this with quality standard metadata registered in catalogs to support search and discovery, map services that can be used by anyone as building blocks in custom web applications, and by developing and hosting web map applications that provide an intuitive interface to display, select, and download many different types of data.

The public can discover bathymetric data from the IHO DCDB Digital Bathymetry viewer (**Figure 3**). There is also the option to display a multibeam bathymetry mosaic of NCEI's bathymetry holdings with elevation values and color shaded relief visualizations as well as the single-beam sounding density. The data sets are freely accessible and the majority can be directly downloaded. Along with displaying the DCDB's bathymetric data holdings, the viewer also shows the locations of data accessible from other repositories (e.g., AusSeabed, Canadian Hydrographic Service, EMODnet Bathymetry, MAREANO) through the ingestion of their web services. Global seafloor mapping campaigns, such as The Galway Initiative and Seabed 2030, can use this viewer as a tool for identifying where data already exist to reduce costly, duplicative surveying efforts. In addition to encouraging countries, organizations, academia, industry, and individuals to contribute their data, the DCDB also strongly encourages other repositories to make their web services available so that their data holdings can be more broadly shared.

EMODnet Bathymetry

An example for a regional bathymetric synthesis for Europe is the European marine observation and data network (EMODnet). This initiative aims at assembling and granting access to European marine data, data products and metadata from diverse sources originating from organizations in countries around European seas (Miguez et al. "EMODnet: Roles and Visions," this issue). The EMODnet Bathymetry Project is an example of a regional approach that develops and provides a bathymetric DTM for the European seas. The DTM is made publicly available for downloading, whereas access to the source data might be restricted. User access to source data, generally at higher resolution than the DTM, might be granted by the data provider directly upon request, depending on the national and/or distribution policy of the hosting organization. With this respect, licenses detailing simple acknowledgment of the source data (more than often through DOI identification) tend to generalize. The grid resolution of the model has increased since the early stages of the project from ∼500 m in 2010, ∼250 m in 2015 to ∼115 m in 2018. Each grid cell has a reference to the source data – bathymetric survey via Common Data Index, composite DTM via the Sextant catalog, and GEBCO in case of gaps – used for determining the water depth. The model is produced from aggregated surveys, collated by a network of contributors from marine research institutes, hydrographic services, government agencies and private companies. In 2018, over 27,000 survey data sets from 42 providers and 140 composite DTMs from 28 providers were included.

The overall EMODnet DTM is generated from the compilation of the data sources available through a commonly adopted methodology (Emodnet Bathymetry, 2009). Data providers provide metadata and make sure their data are processed for erratic soundings and remaining bias. They sample and pre-grid their datasets with a common software tool into data files which are handed over to so-called basin coordinators. The task of the coordinators consists of selecting and then merging selected datasets for their basin, and building the most realistic and accurate regional basin DTM by ensuring a coherent and smooth transition between data sources. Finally, basin coordinators provide their regional DTM to an integrator for composing the full DTM (**Figure 4**).

GMRT

The Global Multi-Resolution Topography (GMRT, Ryan et al., 2009) Synthesis is a global, multi-resolutional Digital Elevation Model (DEM) that includes edited ship-based multibeam data at full spatial resolution (∼100 m in the deep sea). It began as

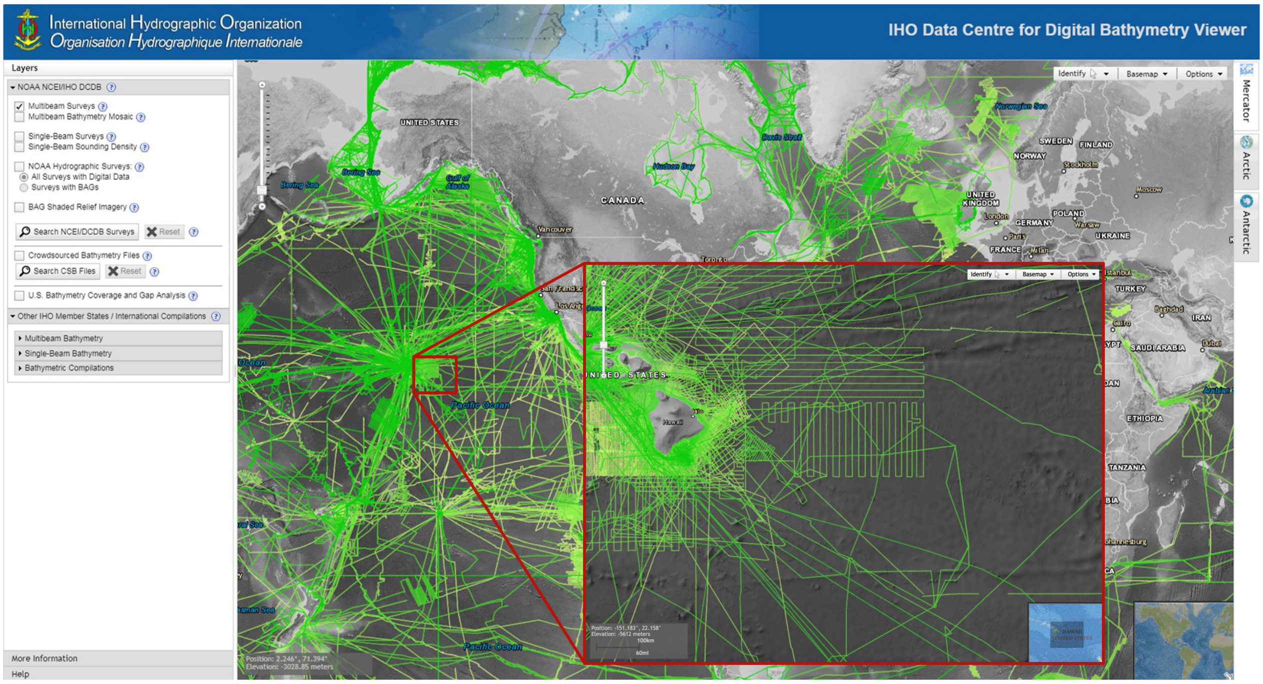

FIGURE 3 | The IHO DCDB Bathymetry viewer which displays bathymetric data holdings (including multibeam bathymetry, shown here) from NOAA NCEI, along with data from other repositories, in order to support ongoing international seafloor mapping efforts.

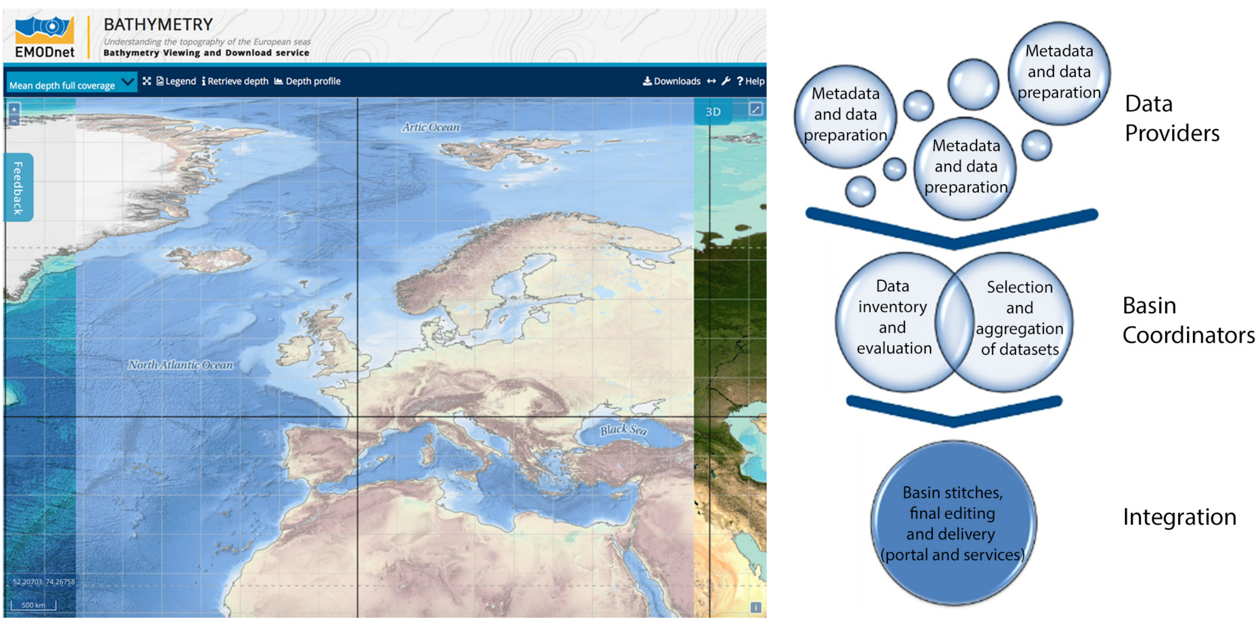

FIGURE 4 | EMODnet Bathymetry grid (version 2018) around the European waters (www.emodnet-bathymetry.eu) and schematic representation of the tasks and roles of each of the contributors of the EMODnet Bathymetry distributed infrastructure.

the Ridge Multibeam Synthesis in 1992 at Columbia University's Lamont-Doherty Earth Observatory and is funded primarily by the United States National Science Foundation (NSF). Its initial purpose was to support research at mid-ocean ridges by synthesizing available bathymetric data into composite grids and images. In 2003, the focus of the compilation was extended to include the Southern Ocean, and GMRT was initiated with a multi-resolutional architecture maintained in three projections.

Since 2005, GMRT has provided free public access to curated gridded ocean bathymetric and terrestrial elevation data in support of global scientific investigations.

A core principle in the design of GMRT is to make elevation data products accessible to specialist and non-specialist users alike while providing full attribution to data sources, and access to source data for advanced users. Access to GMRT is provided through a web application called GMRT MapTool, several web services, and the java-based GeoMapApp desktop application. All of these tools and applications allow access to gridded elevation data in the form of grids, points, and profiles, as well as images and metadata information. Data can be extracted and downloaded from GMRT at user-defined resolutions in a variety of formats.

Terrestrial and bathymetric elevation components combined into GMRT are managed independently, which enables updating content on different schedules. New versions of GMRT are released twice each year and typically $\sim$2 million km^2 of new multibeam data coverage is added annually. Most curatorial effort for GMRT is focused on preparing and integrating multibeam data that are publicly available through the IHO DCDB. Multibeam data processing and curation efforts are focused on the needs of the United States Research Community, with an emphasis on data collected by the United States Academic Research Fleet both during transits and surveys.

Data curation efforts include ping editing, sound velocity corrections, adjustments of attitude sensor offsets, the review and assessment of the data in the context of the high-resolution global compilation, and other adjustments necessary to create high-quality grids of multibeam data at 100 m resolution or better. Source sonar files that were gridded into the compilation are also available for download. GMRT v.3.6, which was released in December 2018, includes edited multibeam data from 1,046 research cruises, conducted between 1980 – 2018 aboard 29 different vessels operated by 26 different institutions (**Figure 5**). This includes more than 225,000 swath data files with more than 31 billion input soundings, which together cover an estimated area of $>$ 31 Million km^2 (8.6%) of the global ocean.

GEBCO

The general bathymetric chart of the oceans (GEBCO) makes available a range of bathymetric data sets and data products. It operates under the joint auspices of the international hydrographic organization (IHO) and the intergovernmental oceanographic commission (IOC) of UNESCO (United Nations Educational, Scientific and Cultural Organization).

The GEBCO chart series has its origins at the beginning of the 20th Century with the initiation of the first chart series by Prince Albert I of Monaco in 1903. Through the 20th Century, five paper editions of the GEBCO chart series were produced (**Figure 6**). In response to the need for digital products, the first edition of the GEBCO Digital Atlas was published on CD-ROM in 1994. In 2003 the Centenary Edition of the GEBCO Digital Atlas was produced and included GEBCO's first gridded bathymetric product, the GEBCO One Minute Grid.

Published in April 2019, GEBCO's latest grid, GEBCO_2019, is a global terrain model at 15 arc-second intervals, which near the equator is about half a kilometer. This is the first GEBCO grid produced under the framework of the Nippon Foundation-GEBCO Seabed 2030 Project. The GEBCO_2019 Grid uses Version 1 of the SRTM (Shuttle Radar Topography Mission)15_PLUS data set (Olson et al., 2014) as its base. This data set is a fusion of land topography with measured and estimated seafloor topography. The data set is augmented with bathymetric data sets developed by the four Seabed 2030 Regional Centers and the international seafloor mapping community.

GEBCO makes available a range of bathymetric products and services, including:

- GEBCO_2019 grid. A global terrain model at 15 arc-second intervals.
- Gazetteer of Undersea Feature Names. A digital data set giving the name, generic feature type and geographic location of names of features on the seafloor.
- GEBCO world map. The map shows the bathymetry of the world's ocean floor in the form of a shaded relief color map. It is based on the GEBCO_08 Grid and can be accessed as an image file.
- GEBCO web map service (WMS). The GEBCO grid is available as a WMS, a means of accessing geo-referenced map images over the internet.
- IHO-IOC GEBCO Cook Book. The Cook Book is a technical reference manual containing information on the development of bathymetric grids and related topics.

The current generation of GEBCO gridded data products is reliant on a range of regional and global mapping projects. GMRT routinely contributes to GEBCO data products. EMODnet Bathymetry is another contributor, together with international bathymetric chart of the arctic ocean (IBCAO) and international bathymetric chart of the southern ocean (IBCSO). Regional grids were also provided for the Caspian, Black, Baltic and Weddell Seas, and for the parts of the Pacific, Atlantic and Indian Oceans by a variety of national agencies and international projects (Weatherall et al., 2015). This collaboration within GEBCO, taking advantage of regional mapping expertise, is fundamental to the production of a global high-quality gridded bathymetry.

INTERNATIONAL COLLABORATION IN GLOBAL MAPPING

From the descriptions of the example initiatives above, synergies between regional and worldwide bathymetric synthesis efforts is self-evident. **Figure 7** shows the general flow of data from data sources into publicly accessible repositories and bathymetric syntheses, and how various synthesis efforts relate to one another. The IHO DCDB serves as the long-term repository for global bathymetric data, that can receive, archive and make available existing data that is not yet shared as well as newly acquired data. Data sources including CSB as well as bathymetric data from the science and the private sector have been described in detail above. In turn, regional and global bathymetric synthesis projects and initiatives provide quality controlled data products, such as GMRT and EMODnet, are important building blocks

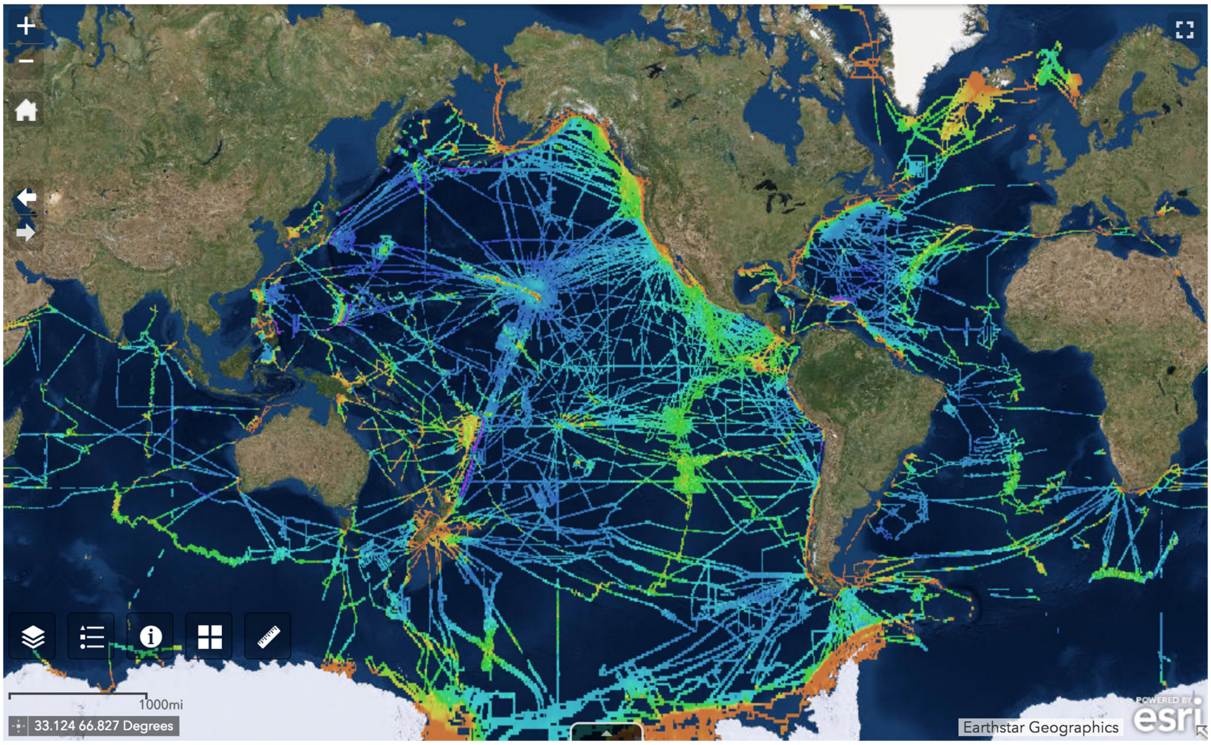

FIGURE 5 | Global extent of curated multibeam sonar data included in GMRT v3.6. Data have been reviewed, processed and gridded at 100 m. Combined with gridded data sets at a variety of resolutions and complemented by the GEBCO basemap, GMRT provides seamless access to global multi-resolutional bathymetric and elevation data.

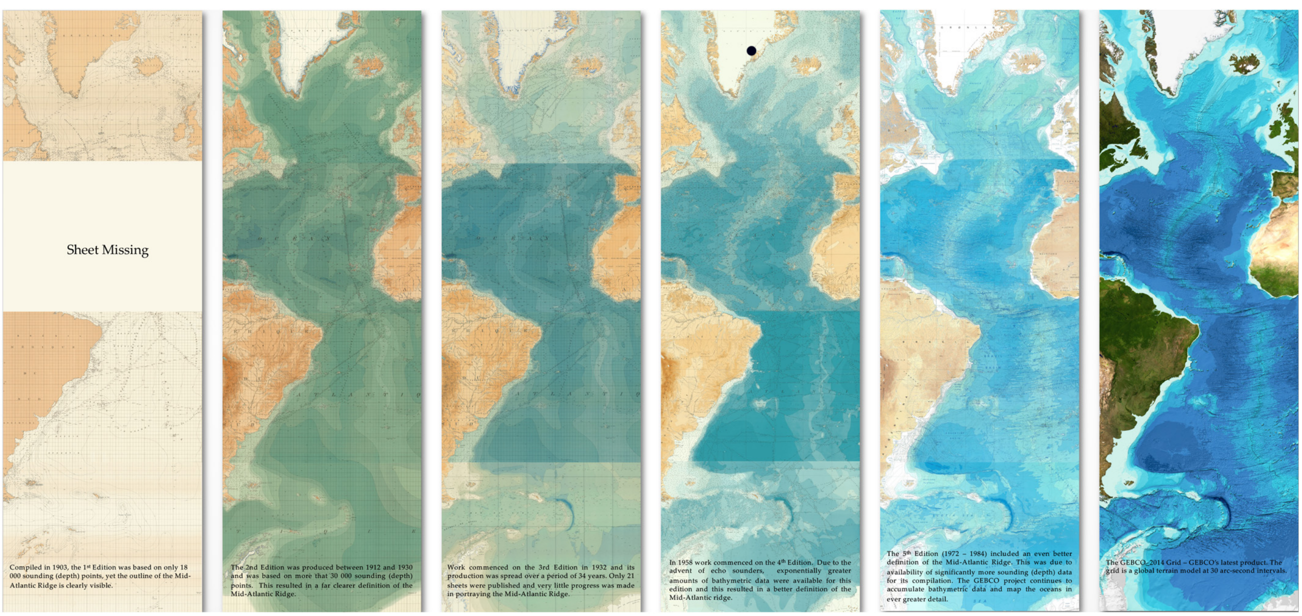

FIGURE 6 | The Mid-Atlantic Ridge as Portrayed in GEBCO charts since 1903 (courtesy of Anthony Pharaoh, IHO).

that contribute to Seabed 2030 and the GEBCO global map. All data products are delivered directly to the public, shared among syntheses, and are ultimately assembled at Seabed 2030 into new regional data products that feed into GEBCO global products. Coordination between and among these efforts is important to avoid duplication of effort, to bring all data sources together

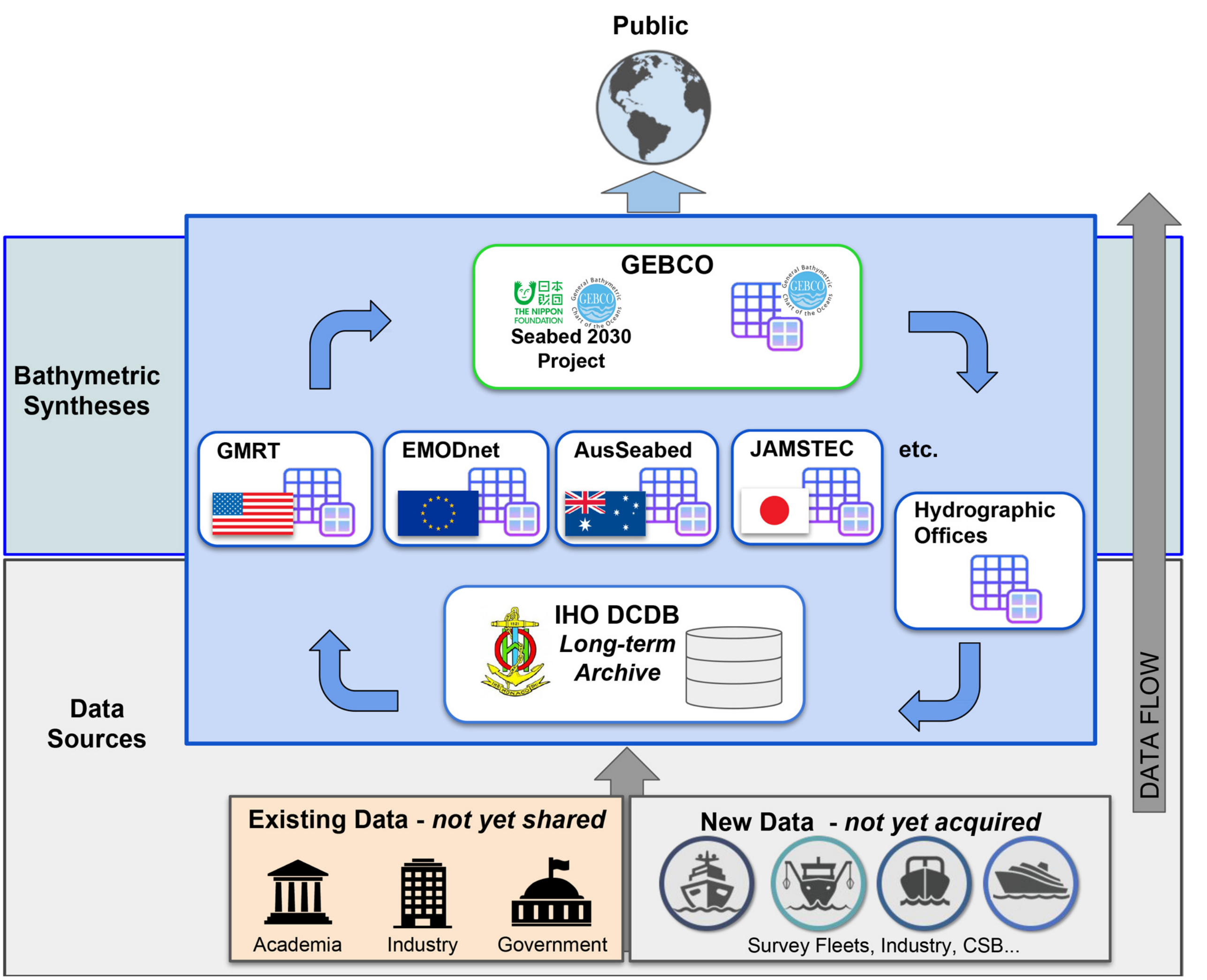

FIGURE 7 | Schematic showing overall flow of data from academic, public and industry sources into public repositories and bathymetric synthesis efforts. This diagram highlights some of the efforts that are underway globally, but is not an exhaustive list of all projects and scales of coordination.

efficiently, and to acknowledge the work and contributions of all efforts and projects.

A SEAFLOOR MAPPING STRATEGY IS NEEDED

Nippon Foundation-GEBCO Seabed 2030 Project

Seabed 2030 is a collaborative project between the Nippon Foundation of Japan and GEBCO. It aims to bring together all available bathymetric data to produce the definitive map of the world ocean floor by 2030 and make it available to all (Jakobsson et al., 2017). The project was launched at the UN Ocean Conference in June 2017 and is aligned with the SDG 14 – Life below water.

The project has established four Regional Centers and a Global Center, is managed by a project director, and is overseen by the GEBCO Guiding Committee. The Regional Centers are responsible for championing mapping activities; assembling and compiling bathymetric information and collaborating with existing mapping initiatives in their regions. The Global Center is responsible for producing and delivering centralized GEBCO/Seabed 2030 products, such as global bathymetric grids. The most recent GEBCO grid, GEBCO_2019, is the first product of the Seabed 2030 Project.

To define the scope of work to populate the map with direct measurement, the project has established a variable-resolution and depth-dependent data scheme to be used for determining "mapped" status (**Table 1**), based on the varying resolution of modern hull-mounted swath bathymetry systems as a function of water depth.

Using this scheme, an analysis of the source data for the GEBCO_2014 grid, i.e., those data included in GEBCO before the start of the Seabed 2030 Project, showed that actual bathymetric data were available for approximately 6.2% of the global ocean

TABLE 1 | Seabed 2030 resolution targets at different depth ranges (Mayer et al., 2018).

Depth	Grid-cell size
0–1,500 m	100 × 100 m
1,500–3,000 m	200 × 200 m
3,000–5,750 m	400 × 400 m
5,750–11,000 m	800 × 800 m

grid cells, 6% of those in international waters, and 5.7% in EEZ. More than two thirds of the data contribution is for grid cells in the 3000–5750 m depth range (**Figure 8**). Using the same scheme, the recently released GEBCO_2019 product has almost 15% of the depth-dependent resolution grid cells based on actual data.

Early priorities of the project include identification of existing data that are not yet included in GEBCO products, using sources outlined earlier. Seabed 2030 is working on building relationships with the survey companies and their customers to release the data they hold or own for use in generating the next generation of GEBCO products. Furthermore, it is critical that a concerted effort is made to identify other available sources and how they can be accessed. Achieving this aim, however, is challenging, especially where the data require to be transferred either via internet or in physical storage devices. First-hand experience in the AusSeabed initiative in Australia has highlighted that transfer of large acoustic seabed data over the internet is difficult for many organizations and can be barrier to accessing these data for producing consistent, consolidated products. In addition, QA of the data prior to submission is necessary to ensure the data can be easily integrated with other existing data. Manual work for preparing and integrating the data and making them available on these end-point portals is another challenge that can become complicated by the variety of proprietary and open formats commonly used in the community.

The Seabed 2030 Project also has, as part of its mission, a requirement to work with the wider bathymetry community to develop strategies for effective mapping. Working through existing partnerships, such as IBCAO and IBCSO, exploration efforts are already being concentrated on those areas with no swath bathymetry coverage (Jakobsson et al., 2012; Arndt et al., 2013). The Regional Mapping Committees being developed in support for the project Regional Centers will aim to expand these efforts to global international waters.

Mapping the Gaps

At present, the chances are still high that any particular multibeam survey will cover unmapped terrain, especially in the deep sea remote from much frequented shipping lanes. In the long term a more strategic approach from the seafloor mapping community is needed, especially in international waters,

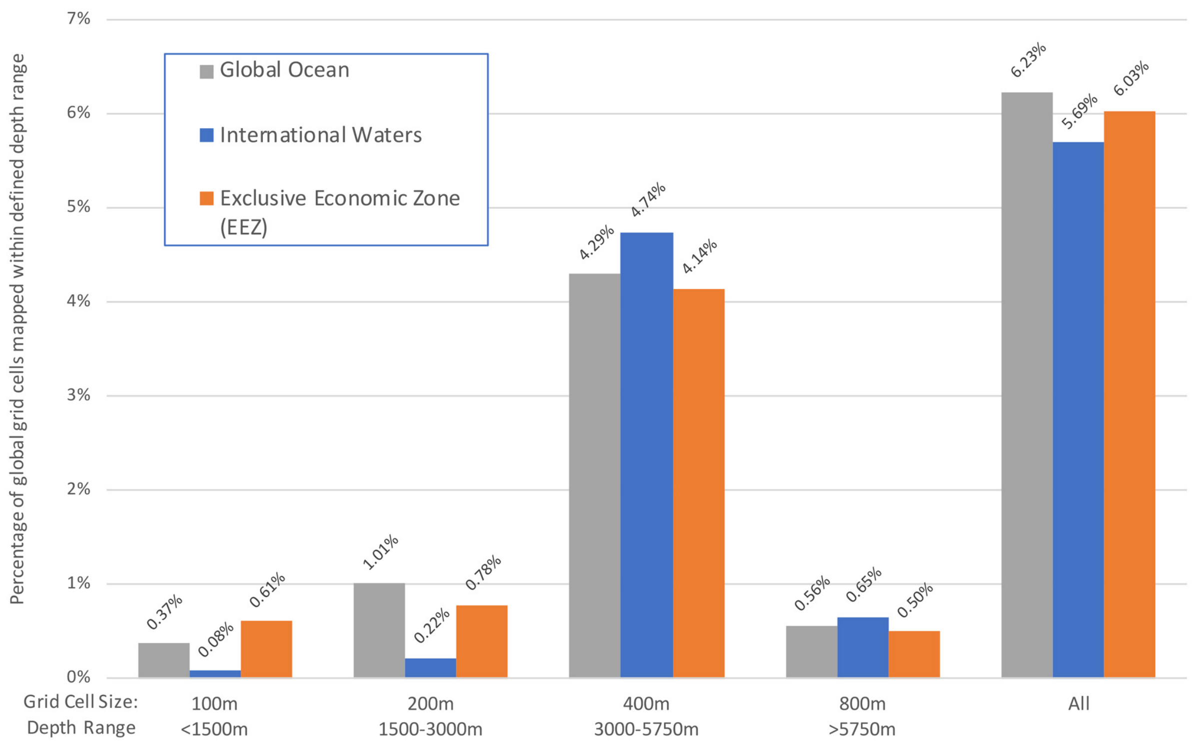

FIGURE 8 | Percentage of the Seabed 2030 target depth-dependent resolution global grid that would be considered "mapped" using the GEBCO_2014 source data, split by contribution from each depth range: calculated as percentage of grid cells in the global ocean, in international waters and in exclusive economic zones (EEZ; all data in Antarctic waters are considered to be outside countries' EEZs).

in order to avoid duplication of effort, efficiently utilize sea-going assets, and to mitigate environmental impacts associated with at-sea operations, such as ocean noise. But how do we choose where to map? An initial attempt has been made by Wölfl et al. (2017) by identifying target areas for future mapping initiatives in the North Atlantic based on multibeam data density and carefully chosen and publicly available marine environmental parameters.

Furthermore, there are regions within the ocean that are of special interest for different kinds of stakeholder groups and it seems reasonable to prioritize those regions. However, it is also important to focus on those regions that are of interest for coastal states that have neither the capabilities nor the facilities to perform large mapping surveys with the systems used by large research institutions and industry. The focus of new technological developments is mainly on automation processes, higher-resolution and enhanced data quality at acquisition. Making the technology affordable for a wider range of user groups currently seems to be of secondary importance but should be tackled as a priority as well.

OUTLOOK AND RECOMMENDATIONS

Understanding the seafloor and associated processes is closely linked to its bathymetry. Mapping the gaps in the world's oceans will better our knowledge of the seafloor and the oceans in general. This knowledge is a significant contribution to the development of sustainable ocean management plans and allows us to respond appropriately to modern challenges, such as environmental degradation in the marine realm, climate change, geohazards and a growing ocean industry. This paper shows the importance of bathymetric data for a variety of applications, and describes the importance of many initiatives and projects that focus on compiling bathymetric data into publicly available archives and syntheses. Although these initiatives have slightly different approaches and goals, they all have in common a commitment to data sharing, and to making data and metadata discoverable and publicly available for all. It is clear that mapping the world's ocean is not a task that can be tackled by one sector or project alone, and that collaboration and coordination across sectors and at a variety of scales is needed. Seabed 2030 is a project borne of this recognition, as presented at the Forum for Future Ocean Floor Mapping, held in Monaco in June 2016. Significant international collaborative efforts already in place within GEBCO, and the bathymetric syntheses described are important components of global mapping initiatives.

The success of future mapping efforts will be reliant on the continuation of these existing efforts and appropriate mapping strategies to provide ever-increasing volumes of high quality data from throughout the global oceans. Increasing the flow of existing, and new, high-quality data through the IHO DCDB and other recognized data centers from across the marine community including the international research community, the commercial sector and via crowdsourcing programs, will provide a huge boost to the data availability. The development of more efficient solutions for data transfer and data processing will be necessary to keep pace with increasing data volumes.

In sum, an increase in data gathering activities combined with effective targeting of future mapping programs and latest technology developments, as well as efficient data processing chains and mapping expertise will be needed if we are ever to deliver knowledge of the seafloor comparable to our knowledge of the land surface.

Based on this paper, the following recommendations regarding the future of seafloor mapping are given:

- Promotion of collaboration and transparency among all sectors.
- Further development of open access data policies for all sectors.
- Provision of bathymetric data sets to publicly accessible online repositories, or lower resolution products or metadata information in case of sensitive data.
- Further strategy development regarding new bathymetric data collection to effectively fill the gaps, leaving a low environmental impact.
- Explore and use opportunities for "underway" data collection, such as transit data and CSB data acquisition.
- Promote standards and establish a QA process for bathymetric data in the community.
- Continuous incorporation of updated bathymetric information into ocean management plans.
- Promote technology developments, regarding enhanced data quality, but also address the needs of low budget user groups by developing low budget solutions.

AUTHOR CONTRIBUTIONS

Structure and basic content of the manuscript came from A-CW and HS. The section 'Bathymetric data repositories and syntheses' was compiled by JJ, TS, VF, and PW. All authors wrote or edited different text sections, reviewed the manuscript and contributed to the responses to the reviewer's comments.

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REFERENCES

Amirebrahimi, S., Picard, K., and Quadros, N. (in press). *Multibeam Echo Sounder Data Acquisition in Australia and Beyond —- User Needs Summary. Record 2019/XX*. Symonston, ACT: Geoscience Australia.

Arndt, J. E., Schenke, H.-W., Jakobsson, M., Nitsche, F. O., Buys, G., Goleby, B., et al. (2013). The international bathymetric chart of the southern ocean (IBCSO) version 1.0 – a new bathymetric compilation covering circum-antarctic waters. *Geophys. Res. Lett.* 40, 1–7. doi: 10.1002/grl.50413

Australian Government (2017). *The Data Behind the Search for MH370*. Available at: https://geoscience-au.maps.arcgis.com/apps/Cascade/index.html?appid = 038a72439bfa4d28b3dde81cc6ff3214 (accessed April 6, 2019).

Bowen, A., Yoerger, D., and Whitcomb, L. (2007). "Hybrid ROV for 11,000 meter operations," in *Proceedings of the Symposium on Underwater Technology and Workshop on Scientific Use of Submarine Cables and Related Technologies*, Tokyo, 206–207.

Calder, B. R., and Mayer, L. A. (2003). Automatic processing of high-rate, high-density multibeam echosounder data. *Geochem. Geophys. Geosyst.* 4

Carlon, R. (2018). Going where no humans should go – unmanned surface vehicles monitoring kilauea volcano lava flow. *Hydro Int.* 22, 23–25.

Chiocci, F. L., Cattaneo, A., and Urgeles, R. (2011). Seafloor mapping for geohazard assessment: state of the art. *Mar. Geophys. Res.* 32, 1–11. doi: 10.1007/s11001-011-9139-8

Clark, M. R., Rouse, H. L., Lamarche, G., Ellis, J. I., and Hickey, C. (2017). *Preparation of Environmental Impact Assessments: General Guidelines for Offshore Mining and Drilling with Particular Reference to New Zealand*. Report No: NIWA Science and Technology Series. Wellington: NIWA.

Eakins, B. W., and Sharman, G. F. (2010). *Volumes of the World's Oceans from ETOPO1*. Boulder, CO: NOAA National Geophysical Data Center.

Ellis, J., Clark, M., Rouse, H., and Lamarche, G. (2017). Environmental management frameworks for offshore mining: the New Zealand approach. *Mar. Policy* 84, 178–192. doi: 10.1016/j.marpol.2017.07.004

Emodnet Bathymetry (2009). *Guidelines for Metadata, Data and DTM QA/QC*. Europe: EMODnet.

Fenty, I., Willis, J. K., Khazendar, A., Dinardo, S., Forsberg, R., Fukumori, I., et al. (2016). Oceans melting greenland: early results from NASA'S ocean-ice mission in greenland. *Oceanography* 29, 72–83. doi: 10.5670/oceanog.2016.100

Glenn, M. F. (1970). Introducing an operational multi-beam array sonar. *Int. Hydrogr. Rev.* 47:35.

Gula, J., Molemaker, M. J., and McWilliams, J. C. (2015). Gulf stream dynamics along the southeastern U.S. Seaboard. *J. Phys. Oceanogr.* 45, 690–715. doi: 10.1175/JPO-D-14-0154.1

Hamilton, T. (2018). *Improving survey efficiency through real-time survey visualization*. Fredericton, NB: Teledyne CARIS Incorporated

Haugen, J. J. (2018). Expanding operations over the horizon - optimising workflows on the maritime information highway. *Hydro Int.* 22, 27–29.

Hein, J. R., Conrad, T. A., and Dunham, R. E. (2009). Seamount characteristics and mine-site model applied to exploration- and mining-lease-block selection for cobalt-rich ferromanganese crusts. *Mar. Georesour. Geotechnol.* 27, 160–176. doi: 10.1080/10641190902852485

Hess, H. H. (1962). "History of ocean basins," in *Petrologic Studies: A Volume to Honor*, eds A. F. Buddington, A. E. J. Engel, H. L. James, and B. F. Leonard (Boulder, CO: Geological Society of America), 599–620. doi: 10.1130/petrologic.1962.599

Howell, K. L., Holt, R., Endrino, P., and Stewart, H. (2011). When the species is also a habitat: comparing the predictively modelled distributions of *Lophelia pertusa* and the reef habitat it forms. *Biol Conserv.* 144, 2656–2665. doi: 10.1016/j.biocon.2011.07.025

Huvenne, V. A. I., Robert, K., Marsh, L., Lo Iacono, C., Le Bas, T. P., and Wynn, R. B. (2018). "ROVs and AUVs," in *Submarine Geomorphology*, eds A. Micallef, S. Krastel, and A. Savini (Heidelberg: Springer), 93–108.

IHO and IOC (2018). *The IHO-IOC GEBCO Cook Book*. Monaco: IHO.

International Hydrographic Bureau (2008). *IHO Standards for Hydrographic Surveys*, 5th Edn. Monaco: IHO.

Irish, J. L., and White, T. E. (1998). Coastal engineering applications of high-resolution lidar bathymetry. *Coast. Eng.* 35, 47–71. doi: 10.1016/S0378-3839(98)00022-2

Jakobsson, M., Allen, G., Carbotte, S. M., Falconer, R., Ferrini, V., Marks, K., et al. (2017). *The Nippon Foundation - GEBCO - Seabed 2030: Roadmap for Future Ocean Floor Mapping*. Available at: https://www.gebco.net/documents/seabed_2030_roadmap_v10_low.pdf (accessed July 27, 2018).

Jakobsson, M., Mayer, L., and Armstrong, A. (2003). Analysis of data relevant to establishing outer limits of a continental shelf under law of the sea article 76. *Int. Hydrogr. Rev.* 4, 1–18.

Jakobsson, M., Mayer, L. A., Coakley, B. J., Dowdeswell, J. A., Forbes, S., Fridman, B., et al. (2012). The international bathymetric chart of the arctic ocean (IBCAO) version 3.0. *Geophys. Res. Lett.* 39:L12609. doi: 10.1029/2012GL052219

Kelley, C., Kerby, T., Sarradin, P., Sarrazin, J., and Lindsay, D. J. (2016). "Submersibles and Remotely Operated Vehicles," in *Biological Sampling in the Deep Sea*, eds M. R. Clark, M. Consalvey, and A. A. Rowden (Hoboken, NJ: Wiley Blackwell).

Lamarche, G., Orpin, A., Mitchell, J., and Pallentin, A. (2016). "Benthic habitat mapping," in *Biological Sampling in the Deep Sea*, eds M. R. Clark, M. Consalvey, and A. A. Rowden (Hoboken, NJ: Wiley-Blackwell).

Lucieer, V. L., and Forrest, A. L. (2016). "Emerging mapping techniques for autonomous underwater vehicles (AUVs)," in *Seafloor Mapping Along Continental Shelves: Research and Techniques for Visualizing Benthic Environments*, eds W. C. Finkl and C. Makowski (Cham: Springer International Publishing).

Lucieer, V. L., Nau, A. W., Forrest, A. L., and Hawes, I. (2016). Fine-Scale sea ice structure characterized using underwater acoustic methods. *Remote Sens.* 8:821. doi: 10.3390/rs8100821

Lurton, X. (2002). *An Introduction to Underwater Acoustics, Principles and Applications*. Cham: Springer.

Mayer, L. (2006). Frontiers in seafloor mapping and visualization. *Mar. Geophys. Res.* 27, 7–17. doi: 10.1007/s11001-005-0267-x

Mayer, L., Jakobsson, M., Allen, G., Dorschel, B., Falconer, R., Ferrini, V., et al. (2018). The nippon foundation—GEBCO seabed 2030 project: the quest to see the world's oceans completely mapped by 2030. *Geosciences* 8:63. doi: 10.3390/geosciences8020063

Olson, C. J., Becker, J. J., and Sandwell, D. T. (2014). "A new global bathymetry map at 15 arcsecond resolution for resolving seafloor fabric: SRTM15_PLUS," in *Proceedings of the AGU Fall Meeting Abstracts 2014*, San Francisco, CA.

Olson, C. J., Becker, J. J., and Sandwell, D. T. (2016). *SRTM15_PLUS: Data Fusion of Shuttle Radar Topography Mission (SRTM) Land Topography with Measured and Estimated Seafloor Topography (NCEI Accession 0150537). Version* 1.1. Asheville: NOAA National Centers for Environmental Information.

Pe'eri, S., Parrish, C., Azuike, C., Alexander, L., and Armstrong, A. (2014). Satellite remote sensing as reconnaissance tool for assessing nautical chart adequacy and completeness. *Mar. Geod.* 37, 293–314. doi: 10.1080/01490419.2014.902880

Picard, K., Brooke, B. P., Harris, P. T., Siwabessy, P. J. W., Coffin, M. F., Tran, M., et al. (2018). Malaysia Airlines flight MH370 search data reveal geomorphology and seafloor processes in the remote southeast Indian Ocean. *Mar. Geol.* 395, 301–319. doi: 10.1016/j.margeo.2017.10.014

Picard, K., Smith, W. H., Tran, M., Siwabessy, J. P., and Kennedy, P. (2017). Increased resolution bathymetry in the southeast indian ocean. *Hydro International Magazine.* Available at: https://www.hydro-international.com/content/article/increased-resolution-bathymetry-in-the-southeast-indian-ocean (accessed September 28, 2017).

Renard, V., and Allenou, J. P. (1979). SeaBeam multibeam echo sounding in jean charcot: description, evaluation and first results. *Intern. Hydrog. Rev.* 1, 35–67.

Rengstorf, A. M., Mohn, C., Brown, C., Wisz, M. S., and Grehan, A. J. (2014). Predicting the distribution of deep-sea vulnerable marine ecosystems using high-resolution data: considerations and novel approaches. *Deep Sea Res. Part I Oceanogr. Res. Pap.* 93, 72–82. doi: 10.1016/j.dsr.2014.07.007

Rezvani, M.-H., Sabbagh, A., and Ardalan, A. A. (2015). Robust automatic reduction of multibeam bathymetric data based on M-estimators. *Mar. Geod.* 38, 327–344. doi: 10.1080/01490419.2015.1053639

Ryan, W. B. F., Carbotte, S. M., Coplan, J. O., O'Hara, S., Melkonian, A., Arko, R., et al. (2009). Global multi-resolution topography synthesis. *Geochem. Geophys. Geosyst.* 10, 1525–2027. doi: 10.1029/2008GC002332

Sala, E., Lubchenco, J., Grorud-Colvert, K., Novelli, C., Roberts, C., and Sumaila, U. R. (2018). Assessing real progress towards effective ocean protection. *Mar. Policy* 91, 11–13. doi: 10.1016/j.marpol.2018.02.004

Sandwell, D. T., Müller, R. D., Smith, W. H. F., Garcia, E., and Francis, R. (2014). New global marine gravity model from Cryo-Sat-2 and jason-1 reveals buried tectonic structure. *Science* 346, 65–67. doi: 10.1126/science.1258213

Sandwell, D. T., Smith, W. H. F., Gille, S., Kappel, E., Jayne, S., Soofi, K., et al. (2006). Bathymetry from space: rationale and requirements for a new, high-resolution altimetric mission. *C. R. Geosci.* 338, 1049–1062. doi: 10.1016/j.crte.2006.05.014

Santoso, A., Cai, W., England, M. H., and Phipps, S. J. (2011). The role of the indonesian throughflow on ENSO dynamics in a coupled climate model. *J. Clim.* 24, 585–601. doi: 10.1175/2010JCLI3745.1

Smith, W., Marks, K., and Schmitt, T. (2017). Airline flight paths over the unmapped ocean. *EOS* 98

Smith, W. H. F., and Sandwell, D. T. (1997). Global seafloor topography from satellite altimetry and ship depth soundings. *Science* 277, 1957–1962.

Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., et al. (2013). *Climate Change 2013: The Physical Science Basis*. Cambridge: Cambridge University Press.

Theberge, A. E. (1989). "Sounding pole to sea beam," in *Paper Presented at the 1989 ASPRS/ACSM Annual Convention Surveying and Cartography*, (Silver Spring, MD: NOAA Central Library), 334–346.

Thompson, A. F., and Sallée, J.-B. (2012). Jets and topography: jet transitions and the impact on transport in the antarctic circumpolar current. *J. Phys. Oceanogr.* 42, 956–972. doi: 10.1175/jpo-d-11-0135.1

United Nations (1982). *Convention on the Law of the Sea (UNCLOS)*. Available at: http://www.un.org/depts/los/convention_agreements/texts/unclos/unclos_e.pdf (accessed December 10, 1982).

United Nations (2015). *Transforming Our World: the 2030 Agenda for Sustainable Development*. Available at: https://sustainabledevelopment.un.org/post2015/transformingourworld/publication (accessed October 21, 2015).

Urick, R. J. (1983). *Principles of Underwater Sound*, 3rd Edn. New York, NY: McGraw-Hill.

Weatherall, P., Marks, K. M., Jakobsson, M., Schmitt, T., Tani, S., Arndt, J. E., et al. (2015). A new digital bathymetric model of the world's oceans. *Earth Space Sci.* 2, 331–345. doi: 10.1002/2015ea000107

Wilson, M. F. J., O'Connell, B., Brown, C., Guinan, J. C., and Grehan, A. J. (2007). Multiscale terrain analysis of multibeam bathymetry data for habitat mapping on the continental slope. *Mar. Geod.* 30, 3–35. doi: 10.1080/01490410701295962

Wölfl, A.-C., Jencks, J., Johnston, G., Varner, J. D., and Devey, C. D. (2017). Where to go next? Identifying target areas in the north atlantic for future seafloor mapping initiatives. *J. Ocean Technol.* 12, 28–42.

Wynn, R. B., Huvenne, V. A. I., Le Bas, T. P., Murton, B. J., Connelly, D. P., Bett, B. J., et al. (2014). autonomous underwater vehicles (AUVs): their past, presence and future contributions to the advancement of marine geoscience. *Mar. Geol.* 352, 451–468. doi: 10.1016/j.margeo.2014.03.012

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